PB-230 819

LAKE CURRENTS: LAKE MICHIGAN BASIN

Federal Water Pollution Control Administration
Chicago, Illinois

November 1967

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 230 819

TER QUALITY INVESTIGATIONS

KE MICHIGAN BASIN

LAKE CURRENTS

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

A TECHNICAL REPORT CONTAINING BACKGROUND DATA
FOR A WATER POLLUTION CONTROL PROGRAM.

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

GREAT LAKES REGION, CHICAGO, ILLINOIS

NOVEMBER 1967

376

CONTENTS

Chapter Page

Foreword.. xi

1 SUMMARY.. 1

2 PHYSICAL SETTING

Location and Description........................ 4
Previous Studies................................ 6
Geology... 7
Physiography and Sediments...................... 11
Hydrology....................................... 12
Lake Levels..................................... 15

3 INTRODUCTION TO LAKE CURRENT STUDIES

General Considerations.......................... 17
Diffusion....................................... 18
Turbulent Mixing................................ 18
Advection....................................... 21
Meteorology..................................... 22
Possible Fate of Pollutants..................... 23
Previous Studies................................ 24
Procedures...................................... 25
  Temperature Studies........................... 26
  Tracer Methods................................ 26
  Fixed-Position Current Metering............... 26
  Equipment Testing............................. 28
Description of Test Studies..................... 28
  Results of Test Studies....................... 28
Reliability..................................... 30
Mooring Characteristics......................... 31
Operational Characteristics..................... 31
Flow Characteristics............................ 37
Winds and Currents.............................. 37
Correlation Between Meters at one Station....... 38
Significance of Findings........................ 44
Summary of Test Studies......................... 44

4 METHODS FOR MOORINGS, INSTRUMENT CHECKS, FILM PROCESSING AND FILM CONVERSION

Introduction.................................... 46
Mooring Systems................................. 46

CONTENTS (Continued)

Chapter Page

4 METHODS FOR MOORINGS, INSTRUMENT CHECKS, FILM PROCESSING AND FILM CONVERSION (Continued)

Film Processing.................................... 66
Format for Film Reading............................ 75
Tape Data Format................................... 76

5 CURRENT METER FILM PROCESSING

Specifications..................................... 78
Initial Processing.................................. 80
First Pass Program................................. 82
Second Pass Programs............................... 84
  Six-Hour Averages................................ 84
  Histograms....................................... 85
  Envelopes.. 85
Spectral Analysis.................................. 88
  Formulas... 90
  Cross Spectrum................................... 91
Graphing... 92
Third Pass Program................................. 93
  Trajectory Programs.............................. 93
  Maps... 93
Temperature Data................................... 93
Drogue Surveys..................................... 96

6 CURRENT STUDIES

Introduction....................................... 101
Data Compilation................................... 102
Net Flows.. 110
General Circulation Patterns - Surface............. 120
General Circulation Patterns - Subsurface.......... 127
Spectral Analysis.................................. 135
  Summary.. 173
Monthly Histograms................................. 174
Six-Hour Averages.................................. 176
Two-Hour Envelopes................................. 178
Flow at Straits of Mackinac........................ 179
Summary of Lake Currents........................... 179

CONTENTS (Continued)

Chapter Page

7 TEMPERATURE STUDIES

Introduction.. 183
Definitions.. 183
Previous Studies.. 184
Methods of Study.. 186
Instruments.. 186
Bathythermograph Surveys..................................... 189
Temperature Recorder Data.................................... 217
Results - BT Surveys.. 217
Fall, 1961.. 217
Winter, 1961.. 217
Spring, 1962.. 220
Summer and Fall, 1962....................................... 220
Spring, 1963.. 221
Summer, 1963.. 221
Discussion.. 221
Results - Temperature Recorder Data........................... 223
Internal Waves.. 223
Analog Records.. 230
Summary... 230

8 DROGUE STUDIES

Introduction.. 234
Equipment... 234
Field Methods... 238
Analysis Methods.. 240
Description of Experimental Results........................... 240
Characteristics of Diffusion.................................. 254
Theoretical Models of Pollutant Diffusion from Continuous Sources... 281
Prediction of Pollution Distribution.......................... 284
Discussion.. 295
Summary... 295

9 METEOROLOGICAL STUDIES

Introduction.. 297
Instrumentation and Collection of Data........................ 297
Climatology of Surface Pressures and Winds.................... 307
Data Analysis and Discussion.................................. 308
Lake Breeze Phenomenon.. 314

CONTENTS (Continued)

Chapter | Page

9 METEOROLOGICAL STUDIES (Continued)

A Comparison of Lake Wind to Land Wind............. 314
Wind Spectra.. 320
Summary... 324

10 CORRELATION OF WIND, CURRENT, AND TEMPERATURE IN SUMMER... 325

11 RELATIONSHIP TO WATER USE AREAS

Introduction.. 351
Water Use Areas Along Shore......................... 352
Water Use Areas in the Lake......................... 353
Significant Factors................................. 354

ACKNOWLEDGMENTS...................................... 356

REFERENCES... 357

TABLES

Number	Title	Page
2-1	Tributary Inflows	13
2-2	Water Budget for Lake Michigan	14
2-3	Computed Periods of the First Five Modes	16
3-1	Current Meter Readings in Each Quadrant	43
4-1	Specifications of Metering Equipment	65
4-2	Specifications of Mooring Materials	65
4-3	16 mm Film Data Identification Sheet and Log	67
4-4a	Inspection Sheet-Current Meters Tear-Down	68
4-4b	Inspection Sheet-Current Meters Build-Up	69
4-5a	Inspection Sheet-Temperature Recorder Tear-Down	70
4-5b	Inspection Sheet-Temperature Recorder Build-Up	71
4-6a	Inspection Sheet-Wind Recorder Tear-Down	72
4-6b	Inspection Sheet-Wind Recorder Build-Up	73
5-1	Format Six-Hour Averages	86
5-2	Sample Format of Histogram	87
6-1	Timing Accuracy of Clocks	101
6-2	Current Meter Records	105
6-3	Current Meter and Wind Recorder	111
6-4	Questionnaire	113
6-5	Conversion Factors	114
6-6	Drogue Variations	115
6-7	Current Spectra Data	165
6-8	Histogram	175
6-9	Six-Hour Average Winds	177
6-10	Cross Section of the Straits of Mackinac	180
6-11	Average Speed and Direction in the Straits	180
7-1	Degree of Accuracy of Instruments	189
7-2	Temperature Data and Station Location of Cruises	214
7-3	Schedule of Cruises	216
8-1	General Information on Experimental Runs	245
8-2	Values of Characteristics of Diffusion	264
9-1	Lake Michigan Wind Data	299
9-2	Ratio of Buoy and Ship Wind Speeds	311
9-3	Average Deviation of Buoy and Ship Wind Directions	311
9-4	Histogram of Winds - Station 5	312
9-5	Wind Spectra Data	322
10-1	Position of Stations	335
10-2	Correlation Table of Standing Poincaré Waves	348
10-3	Correlation Between Temperature 'Waves' and Currents	349

FIGURES

Number	Title	Page
2-1	Drainage Basin	5
2-2	Geologic Map	8
2-3	Bathymetric and Physiographic Map	9
2-4	Bottom Sediments	10
3-1	Telemetry Current Meter Locations	29
3-2	95 Percent Confidence Limits	32
3-3	Speeds at 18 and 27 Meters	33
3-4	Current Meter Speeds	34
3-5	Direction at 18 and 27 Meters	35
3-6	Direction at 27 and 36 Meters	36
3-7	Histogram of Speed at Three Levels	39
3-8	Savonius Rotor Calibration	40
3-9	Polar Diagram - 18 m.	41
3-10	Polar Diagram - 27 m.	42
4-1	Station Diagram - Summer	47
4-2	Typical Current Station	48
4-3	Recovery Buoy System	50
4-4	Link and Line Storage Case	51
4-5	Typical Current Station - Winter	52
4-6	Subsurface Buoy	53
4-7	Temperature Recorder	54
4-8	Current Meter	55
4-9	Anchors	56
4-10	Instrument Line Components	57
4-11	Rigid Bridle	58
4-12	Navigation Light	59
4-13	Wind Recorder	60
4-14	Heavy Duty Anemometer	61
4-15	Instrument Buoy	62
4-16	Buoy and Float	63
4-17	Camera Loading Diagram	74
5-1	Compass and Vane Angle Deflection	82
5-2	Major Axis of Positive Angles	83
5-3	Inertial Type Rotation	89
5-4	Format of Trajectory Program	94
5-5	Format of Mapping Program	95
6-1	Histogram of Blurring	103
6-2	Lake Michigan Current Meter Station Locations	104
6-3	Current Direction Phase Shift - Station 8	117
6-4	Winter Circulation, N-NW Winds	121
6-5	Winter Circulation, S-SW Winds	122
6-6	Summer Circulation, N-NE Winds	123
6-7	Summer Circulation, S-SW Winds	124

FIGURES (Continued)

Number	Title	Page
6-8	Subsurface Net Flows, 60 Meters	128
6-9	Subsurface Net Flows, 90 Meters	129
6-10	Subsurface Net Flows, 120 Meters	130
6-11	Subsurface Net Flows, 150 Meters	131
6-12	Subsurface Net Flows, 180 Meters	132
6-13	Subsurface Net Flows, 210 Meters	133
6-14	Subsurface Net Flows, 240 Meters	134
6-15	Winter Current Spectra - Lake Michigan	136
6-16	Summer Current Spectra - Lake Michigan	137
6-17	Spectra of Components, Sta. 9, 15 m.	138
6-18	Spectra of Components, Sta. 9, 30 m.	139
6-19	Spectra of Components, Sta. 9, 90 m.	140
6-20	Spectra of Components, Sta. 10, 10 m.	141
6-21	Spectra of Components, Sta. 10, 15 m.	142
6-22	Spectra of Components, Sta. 13, 10 m.	143
6-23	Spectra of Components, Sta. 13, 30 m.	144
6-24	Spectra of Components, Sta. 13, 60 m.	145
6-25	Spectra of Components, Sta. 17, 10 m.	146
6-26	Spectra of Components, Sta. 20, 15 m.	147
6-27	Spectra of Components, Sta. 20, 90 m.	148
6-28	Spectra of Components, Sta. 29, 15 m.	149
6-29	Spectra of Components, Sta. 29, 60 m.	150
6-30	Spectra of Components, Sta. 31, 10 m.	151
6-31	Spectra of Components, Sta. 31, 15 m.	152
6-32	Spectra of Components, Sta. 31, 22 m.	153
6-33	Spectra of Components, Sta. 31, 30 m.	154
6-34	Spectra of Components, Sta. 40, 60 m.	155
6-35	Spectra of Components, Sta. 41, 10 m.	156
6-36	Spectra of Components, Sta. 41, 90 m.	157
6-37	Spectra of Components, Sta. 41, 120 m.	158
6-38	Spectra of Components, Sta. 54, 10 m.	159
6-39	Spectra of Components, Sta. 54, 22 m.	160
6-40	Spectra of Components, Sta. 54, 30 m.	161
6-41	Spectra of Components, Sta. 61, 10 m.	162
6-42	Spectra of Components, Sta. 61, 15 m.	163
6-43	Spectra of Components, Sta. 61, 22 m.	164
6-44	Flows at Straits of Mackinac	181
7-1	Density of Fresh Water	185
7-2	Bathythermograph	187
7-3	Temperature Recorder	188
7-4	Lake Michigan Cruise No. 1	190
7-5	Lake Michigan Cruise No. 2	191
7-6	Lake Michigan Cruise No. 3	192
7-7	Lake Michigan Cruise No. 4	193

FIGURES (Continued)

Number	Title	Page
7-8	Lake Michigan Cruise No. 5	194
7-9	Lake Michigan Cruise No. 6	195
7-10	Lake Michigan Cruise No. 6	196
7-11	Lake Michigan Cruise No. 6	197
7-12	Lake Michigan Cruise No. 6	198
7-13	Lake Michigan Cruise No. 7	199
7-14	Lake Michigan Cruise No. 8	200
7-15	Lake Michigan Cruise No. 10	201
7-16	Lake Michigan Cruise No. 11	202
7-17	Lake Michigan Cruise No. 12	203
7-18	Lake Michigan Cruise No. 13	204
7-19	Lake Michigan Cruise No. 13	205
7-20	Lake Michigan Cruise No. 14	206
7-21	Lake Michigan Cruise No. 15	207
7-22	Lake Michigan Cruise No. 16	208
7-23	Lake Michigan Cruise No. 17	209
7-24	Lake Michigan Cruise No. 18	210
7-25	Station Locations, Cruise No. 50	211
7-26	Station Locations, Cruise No. 51	212
7-27	Station Locations, Cruise No. 52	213
7-28	Lake Michigan Temperature Recorder Locations	218
7-29	Formation of the Thermocline	224
7-30	Internal Waves at Station 9, 15 m.	225
7-31	Spectra of Temperature Records - 1963, Sta. 31 and 41	227
7-32	Spectra of Temperature Records - 1963, Sta. 8 and 11.	228
7-33	Spectra of Temperature Records - 1963, Sta. 4 and 20.	229
7-34	Temperature Changes at Station 8	231
8-1	Drogue	235
8-2	Drogue Surface Floats	237
8-3	Reference Marker	239
8-4	Map - Runs 1 and 2	241
8-5	Map - Runs 3 and 4	242
8-6	Map - Runs 5 and 6	244
8-7	Drogue Positions (Run 1)	246
8-8	Drogue Positions (Run 2)	247
8-9	Drogue Positions (Run 3)	248
8-10	Drogue Positions (Run 5)	249
8-11	Drogue Positions (Run 6)	250
8-12	Time Variation (Runs 1 and 2)	251
8-13	Time Variation (Run 3)	252
8-14	Time Variation (Runs 5 and 6)	253
8-15	Movement of Drogues and Wind Track (Run 1)	255
8-16	Movement of Drogues and Wind Track (Run 2)	256

FIGURES (Continued)

Number	Title	Page
8-17	Movement of Drogues and Wind Track (Run 3)	257
8-18	Movement of Drogues and Wind Track (Run 5)	258
8-19	Movement of Drogues and Wind Track (Run 6)	259
8-20	Standard Deviation of Drogues to Initial Position (Runs 1 and 2)	261
8-21	Standard Deviation of Drogues to Initial Position (Run 3)	262
8-22	Standard Deviation of Drogues to Initial Position (Runs 5 and 6)	263
8-23	Mean Separation (Runs 1 and 2)	266
8-24	Mean Separation (Runs 2 and 3)	267
8-25	Mean Separation (Runs 3 and 5)	268
8-26	Mean Separation (Run 6)	269
8-27	Mean Square Separation Versus Time (Runs 1 and 2)	271
8-28	Mean Square Separation Versus Time (Runs 2 and 3)	272
8-29	Mean Square Separation Versus Time (Runs 3 and 5)	273
8-30	Mean Square Separation Versus Time (Run 6)	274
8-31	Standard Deviation-Pair Versus Time (Run 1)	276
8-32	Standard Deviation-Pair Versus Time (Run 2)	277
8-33	Standard Deviation-Pair Versus Time (Run 3)	278
8-34	Standard Deviation-Pair Versus Time (Run 5)	279
8-35	Standard Deviation-Pair Versus Time (Run 6)	280
8-36	Steady-State Distribution of Concentration ($\omega_1 = 0.2$)	287
8-37	Steady-State Distribution of Concentration ($\omega_1 = 0.4$)	288
8-38	Relative Concentration ($y_1 = 0$)	289
8-39	Relative Concentration ($y_1 = 2$)	290
8-40	Relative Concentration ($y_1 = 4$)	291
8-41	Non-Steady Distribution ($y_1 = 0(0.2)$)	292
8-42	Non-Steady Distribution ($y_1 = 0(0.4)$)	293
8-43	Relative Concentration	294
9-1	Network Stations	298
9-2	Calibration	302
9-3	Instrument Buoy	303
9-4	6-Hour Averages - Station 5	305
9-5	2-Hour Envelope	306
9-6	Lake Michigan Printout	309
9-7	Current Trajectories	313
9-8	Weather Map 12C, August 20, 1963	315
9-9	Weather Map 12C, August 21, 1963	316
9-10	2-Hour Envelope - Station 8	317
9-11	2-Hour Envelope - Station 18	318

FIGURES (Continued)

Number	Title	Page
9-12	Lake Michigan Versus Shore Wind Direction............	319
9-13	Lake Michigan Versus Shore Wind Speed...............	321
9-14	Spectra, Station 13.................................	323
10-1	Temperature Distribution Between Milwaukee and Muskegon..	326
10-2	Distribution of 10° Isotherm, Milwaukee to Muskegon..	328
10-3	Qualitative Representation of Kelvin and Sverdrup Waves...	329
10-4	Transverse Standing, Kelvin, Sverdrup and Poincaré Waves...	330
10-5	Comparison of Lake and Land Wind Speeds.............	331
10-6	Comparison of Lake and Land Wind Speeds.............	332
10-7	Wind, Temperature, and Currents - Station 15.........	336
10-8	Wind, Temperature, and Currents - Station 15.........	337
10-9	Wind, Temperature, and Currents - Station 17.........	338
10-10	Wind, Temperature, and Currents - Station 17.........	339
10-11	Wind, Temperature, and Currents - Station 17.........	340
10-12	Wind, Temperature, and Currents - Station 20.........	341
10-13	Wind, Temperature, and Currents - Station 20.........	342
10-14	Wind, Temperature, and Currents - Station 20.........	343
10-15	Sections Across a Uninodal and a Trinodal Wave.......	344

FOREWORD

In 1960 the Federal Government undertook the task of determining the sources of wastes responsible for degrading the quality of Great Lakes waters, evaluating the effects of such wastes on the quality and uses of the receiving waters, and developing comprehensive water pollution control programs to enhance and protect their quality. To better understand the physical mechanisms by which pollution-laden waters mix with and are transported by lake currents, an extensive study of these phenomena was incorporated into the investigations. An account of part of this monumental task -- relating to circulation, diffusion, and seasonal changes in physical parameters in Lake Michigan -- is given in the report which follows.

In view of the oceanographic scale of the study, instruments and data processing techniques recently developed for ocean investigations were utilized. A lake-wide deployment of recording instruments produced a long series of records of current and water temperature at several depths from more than 30 stations covering all of Lake Michigan. Wind was also recorded at some of the stations. This is the first occasion on which physical events and processes in so large a natural water body, fresh or marine, have been monitored for an interval of nearly 2 years with so close a network of recorders.

While the need to solve immediate practical problems provided the impetus for the investigation, the invested effort has yielded much new information of scientific interest, and this provides yet another example of the advantages to be gained by close association between applied and so-called pure research.

Practical questions of great urgency concerning the fate of the Great Lakes await answers; and it is in the light of these concerns that the appearance of this report must chiefly be welcomed. Its findings -- on such matters as the dominant summer and winter circulation patterns, the differences between inshore and offshore current regimes, and the rates of turbulent dispersal -- will have important bearing on the interpretations to be placed on water quality changes. There can be no doubt that this and subsequent reports by the Great Lakes-Illinois River Basins Project will be indispensable source books for future water planning in the Great Lakes region and for other scientific and engineering studies.

Clifford H. Mortimer, D.Sc., F.R.S.
Director, Center for Great Lakes Studies
University of Wisconsin-Milwaukee

CHAPTER 1

SUMMARY

Lake Michigan is the third largest of the Great Lakes and the only one lying wholly within the United States. It has a surface area of 58,016 square kilometers, an average depth of 84 meters, and a total volume of 4,878 cubic kilometers. In general, the Lake is oriented along the north-south axis, the northern part of the Lake curving gently to the northeast. The Lake is divided into two basins by two parallel ridges running in an easterly direction from Milwaukee to Grand Haven. The southern basin is smaller and shallower than the northern basin with a maximum depth of 160 meters. The northern basin is longer and narrower. In it is located the deepest point in the Lake, 281 meters.

The energy inputs into the Lake responsible for mixing and movement of its waters are derived almost exclusively from meteorological disturbances. Whereas in small lakes the transfer of energy through wind stress tends to drive the surface water out, in Lake Michigan this process is complicated by such factors as the Coriolis effect of the earth's rotation, nonuniformity of wind stress, and by the variation in atmospheric pressure on the water surface from the progression of high and low barometric pressure areas passing over the Lake. Although there are an infinite variety and frequent changes in both direction and magnitude of energy input, certain patterns of water movement have been observed. These patterns result from the fact that seasonally there is a dominance of winds from one general direction.

Both water movements and rate of mixing are materially influenced by the formation of thermoclines, or zones of temperature transition between two layers of water which differ in temperature and density. Once stabilized at depths which prevent storm turbulence interruption, summer thermoclines effectively prevent mixing of waters of the epilimnion (upper layer) with those of the hypolimnion (bottom waters). Reverse thermoclines, involving very small density changes, are found in winter but usually at greater depths than in summer because they offer less resistance to wind mixing.

Thermal bars, phenomena resulting from a difference in temperature between adjacent waters along a vertical plane, occur both in the spring and in the fall in shallow waters parallel to the shoreline. Like the thermocline, a thermal bar prevents mixing between the shallow waters along the shore and the deeper Lake waters.

Temperature records from many of the stations showed that internal waves were almost always present on the thermocline. Spectral analysis of the temperature clearly established several frequencies for these waves, the most dominant being in the 16 to 18-hour frequency. This corresponds closely to the inertial period for the latitude. The inertial period is related to the rotation of the earth, being 24 hours at 30° latitude and varying as the sine of the latitude.

Four basic patterns of water movements occur in the upper layers, two in winter and two in summer. Each current pattern is somewhat modified by the nearshore currents. The shore currents appear to be dominated by the prevailing or net winds. One winter pattern shows the influence of north-northwest winds. The currents generally move southerly along the east shore and northerly along the west shore. There is a rotation in the southern basin with some of the northerly flow moving eastward in the general area of Milwaukee and joining the southerly flow along the east side below Grand Haven. A similar gyre, elongated in shape, exists in the northern basin. It extends from an area north of Milwaukee to the Straits of Mackinac and also circulates in a clockwise direction. This pattern may be expected during 25 to 30 percent of the year.

The other winter pattern occurs only 20 to 25 percent of the year, principally between January and April. In this pattern the gyres in the northern and southern basins are reversed and rotate counterclockwise with principal flows north along the east shore and south along the west shore.

The dominant summer pattern is created by south-southwest winds occurring nearly 40 percent of the year. Much obscured by rotating currents associated with internal waves, the picture of general circulation may be defined roughly as follows: In the southern basin the counterclockwise gyre exists, but inshore currents on both the east and west shores are northward. The northerly flow along the west shore is weaker and undoubtedly fed by westerly flows in the deeper waters. In the northern basin, the dominant flow is southward in the center of the Lake. This southward flow splits above Milwaukee, one part moving east and north along the east shore, and the other moving west and north along the western shore.

When under the occasional dominance of north-northeast winds, the southern basin gyre continues in its previous counterclockwise direction, but the inshore currents along both the east and west shores then move southward. This pattern, again obscured by rotating currents associated with internal waves, occurs about 10 percent of the year. At such times, southward currents also prevail along both shores in the northern basin, and there is a narrow current south in the central part of the northern basin. This splits above Milwaukee to feed narrow currents running northward on both sides of the central southern movement and between the southerly currents along both shores.

Drogues were used to track water masses in the following diffusion studies: In southern Lake Michigan, at the mouth of the Detroit River in Lake Erie and near Cleveland, Ohio in Lake Erie. A special study was also conducted in Lake Michigan in September 1961, following the release of a large mass of polluted water into the Lake from the Chicago River mouth. This latter study did not use drogues; instead, a grid of sampling points was established in the area and the water movement and mixing were established on the basis of coliform analyses.

Based on the diffusion studies it was concluded that mixing in shallow shore waters with steady wind velocities in the range of 300 to 400 cm/sec is relatively slow. Under such conditions pollutants discharged into the Lake can travel several miles relatively undiluted. Although the extent of mixing can be calculated, the duration of winds having the particular direction and velocity to produce maximum effects at a particular water use point is less certain.

The complexity of the interplay of forces providing energy inputs into Lake Michigan has prevented the development of mathematical models describing the relationship between the direction and velocity of winds over land with the associated water movements. Nevertheless, knowledge of the current patterns described herein should be helpful in the site selection and design of water intakes and waste outlet installations. Additional more specific data are available where such a site is near a current meter station. However, special studies or investigations should be undertaken to confirm the validity of the data at the chosen site, since most of the current metering stations were set in deeper waters and would not necessarily reflect the local effects of irregularities along the shoreline; nor would they detect the presence of a thermal bar which could prevent the mixing of nearshore with offshore waters.

CHAPTER 2

PHYSICAL SETTING

Location and Description

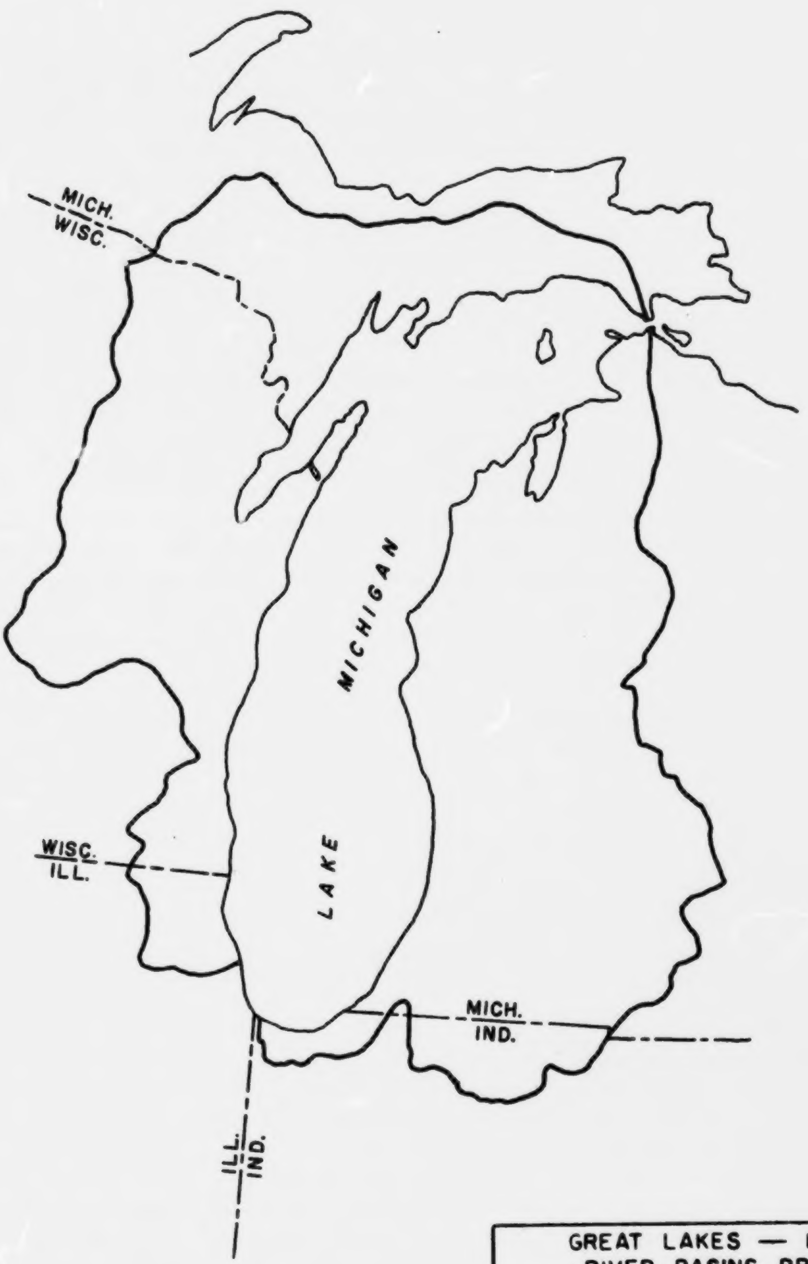
Lake Michigan is the only one of the Great Lakes that lies wholly within the boundaries of the United States, but it is so large and extends so far into the United States that it forms a small interior sea. The Lake has a surface area of 58,016 square kilometers (km^2), which is equal in area to the combined States of New Hampshire, Massachusetts, Connecticut, and Rhode Island. It has an average depth of 84 meters (m) and a maximum depth of 281 m. The deepest portion of the Lake is 105 m below sea level. Its length is 494 km and its width is 190 km; the total length of shoreline is 2,673 km and the total volume of water is 4,878 cubic kilometers (km^3). The mean-water surface elevation of Lake Michigan is 176.5 m above sea level. The range of monthly mean elevation is 2 m and the average seasonal fluctuation is 0.30 m.

The States bordering Lake Michigan are Illinois, Indiana, Michigan, and Wisconsin. Major cities located on the Lake are Chicago, Illinois; Gary, Indiana; Racine, Wisconsin; Milwaukee, Wisconsin; and Muskegon, Michigan. The 1960 population of the basin was approximately 5.7 million, about 3.2 percent of the United States. These figures do not include the Chicago region which is located in the Illinois River Basin, Figure 2-1.

The climate of the Lake Michigan Region is typical humid continental with severe winters and warm summers. Temperatures increase from north to south. The greatest extremes occur during the winter months. The January means for Chicago and Green Bay, respectively, are 5.5° and -9.8°C. The July means for Chicago and Green Bay, respectively are 22.5° and 21.7°C. The mean annual temperature of Chicago is 9.5°C, whereas to the north at Green Bay it is 6.6°C.

The mean annual precipitation for the region is approximately 77.2 centimeters (cm), and is higher between April and September than between October and March (USLS, 81). The east side of Lake Michigan receives more precipitation than the western side. Precipitation increases with ground elevation in the basin and averages approximately 10 percent higher over upland areas than over the lakes which are a hundred meters lower (Day, 24).

Intralake shipping on the Great Lakes ceases around December 1 each year because of ice conditions. Lake Michigan does not usually


MICH.
WISC.
LAKE MICHIGAN
WISC.
ILL.
MICH.
IND.
ILL.
IND.

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

**DRAINAGE BASIN
of
LAKE MICHIGAN**

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 2-1

freeze over, except during severe winters, but ice conditions in such areas as the Straits of Mackinac, eastern Lake Erie, the Welland Canal, and the St. Lawrence River close passage to all ships. Winter navigation on Lake Michigan consists of car-ferries and fuel vessels operating regularly between the major ports. The ice builds up from shore and later may break off and become drift ice. During severe winters, Lake Michigan has been known to freeze completely over, for instance during February 1963. Upon breakup, drifting ice usually piles up, in constricted areas, into ridges and windrows as high as 10 m and 13 or more m in depth.

The opening date of navigation is usually early April, but has been as late as early May.

Previous Studies

The first study of currents in Lake Michigan was conducted by Harrington in 1895 (36). Field work for his report was carried out from 1892 to 1894. Harrington released approximately 1,500 drift bottles at various points in the Lake and recovered 203 of them at their points of stranding on the shores. From these returns, a chart was made showing the surface currents. This chart showed two counterclockwise gyres making up the principal circulation systems; one in the southern basin, and a more elongated one in the northern part of the Lake. A much smaller elongated clockwise gyral flow system was located along the western shore near Milwaukee.

Townsend (78), in 1916, criticized the findings of Harrington, and pointed out that since only the point of release and the point of recovery of drift bottles are known, it is not possible to know the path taken by the bottles. In 1932-36, Deason (25) studied Lake Michigan currents using drift bottles, and his conclusions generally followed Harrington's.

Church (18, 19), in 1942 and 1945, made a comprehensive study of the annual temperature cycle in a number of cross-sections of Lake Michigan. His temperature data tended to support Harrington. In 1954-55, the U. S. Bureau of Commercial Fisheries completed an intensive study of surface currents using drift bottles and drift cards (Johnson, 45). Out of 6,000 releases, 3,000 were recovered. The results of the 1954 study were inconclusive; in general, however, the drift was west to east and north to south movements about equal in magnitude. A similar pattern was found in 1955, except that the drift in the eastern areas was mainly from the south. Ayers et al., (2) 1958, published the results of a series of synoptic surveys completed in 1955, in which they used drift bottles and applied a modification of the dynamicheights method to determine the circulation of Lake Michigan. The results of the drift bottle study showed good agreement with Harrington's study.

As pointed out by Ayers et al., the winds were westerly, which he considers as being the norm for the summer months. Except for Church (19) 1942, inferred from temperature, none of the above researchers reported on wintertime lake circulation.

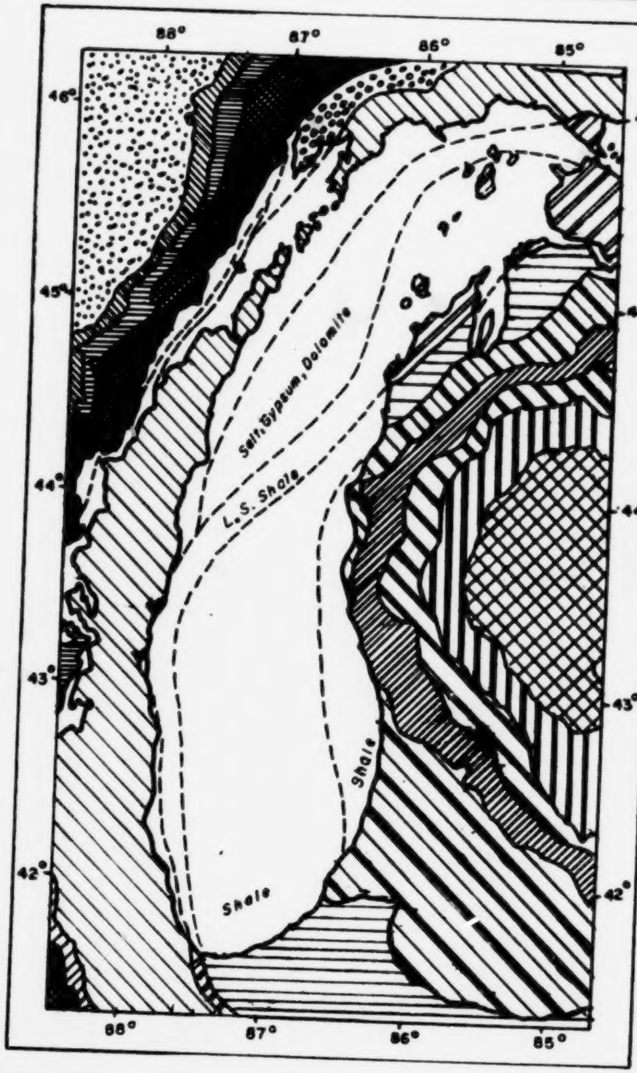
Geology

Various phases of the geology of Lake Michigan have been reported, but only the more recent will be mentioned here (see Figures 2-2, 2-3, and 2-4).

In 1958, Hough (40) showed that glacial till is a common bottom material and that wave action in shallow water has winnowed out the finer grains, leaving a concentration of gravel just offshore. Shepard (71), pointed out that glacial erosion at the north end of the Lake is indicated by fiord-like valleys, by rocky islands, and by complex bottom topography. Thwaites (77) related the ridges around the lake shore and on its floor to the presence of resistant dolomites, limestones, and sandstones, and the deeper areas to less-resistant shales and evaporites. The position and strike of the outcrop of these alternating beds of hard and soft strata are controlled by the southeasterly dip into the structural basin that underlies the State of Michigan. Emery (30) described the bathymetry and bottom deposits of Lake Michigan.

Lake Michigan is located entirely within a region of Paleozoic rocks (Fig. 2-2) that form part of a structural basin centered in the State of Michigan. To the northwest are Pre-Cambrian rocks that comprise part of the Canadian Shield, onto which the Paleozoic rocks onlap. Due to the structure of the area, the oldest rocks crop out in the west; the rocks become progressively younger toward the structural basin. The strike of these rocks generally follows the long axis of the Lake.

In the north, the floor of the Lake is made up of evaporites, limestones, and shales. The southern Lake basin is floored by shales. Very few outcrops of these rocks exist, however, because they are mantled by glacial debris deposited during the Pleistocene Epoch. Although the Lake Michigan area has been an area of low topography with numerous invasions of the sea, it was the glaciers that formed during the Pleistocene Epoch which shaped the lake itself. These glaciers developed to the north and migrated southward, gouging out the Lake Michigan Basin. The topography of the region has been little modified since.



LEGEND

Symbol		Age	Lithology
▦	U. M.	PENNSYLVANIAN	SANDSTONE, SHALE
	L. M.		SHALE, SANDSTONE
▥	L.		SHALE, SANDSTONE
▧	M. M.	MISSISSIPPIAN	DOLOMITE, SHALE
■	L. M.		SANDSTONE
▨	L.		SHALE
▥	U.	DEVONIAN	SHALE
▨	M.		LIMESTONE, SHALE
▧	U.	SILURIAN	SALT, GYPSUM, DOLOMITE
▨	M.		DOLOMITE
░	L.		SHALE, DOLOMITE
▨	U.	ORDOVICIAN	SHALE
■	M.		SHALE, LIMESTONE
▤	L.		DOLOMITE, SHALE
▩	U.	CAMBRIAN	SANDSTONE, SHALE
	U.	HURONIAN	VARIOUS ROCKS
	M.		VARIOUS ROCKS
	L.		VARIOUS ROCKS
░	PRE-CAMBRIAN		INTRUSIVES

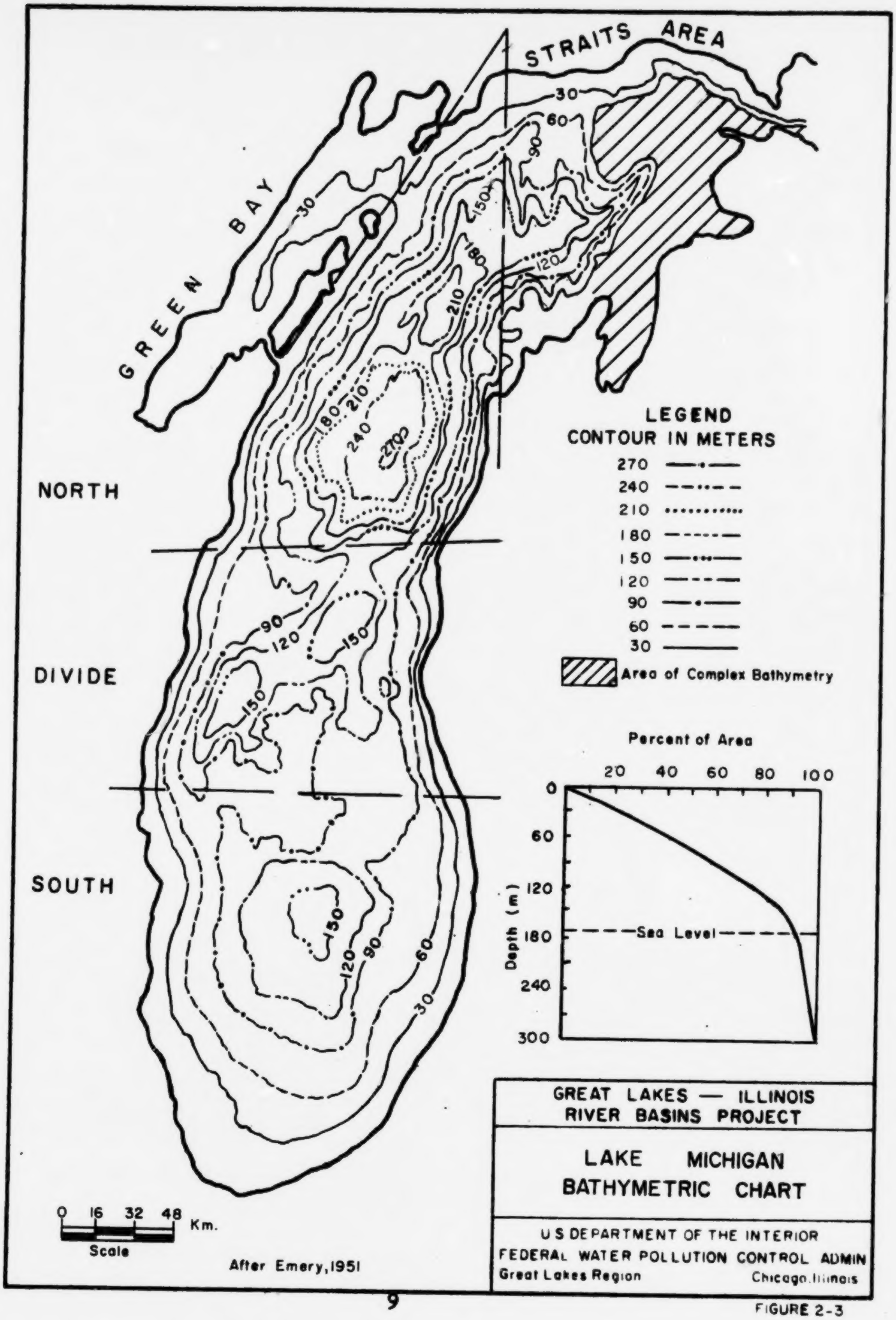
After Emery, 1951 (30)

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

GEOLOGIC MAP

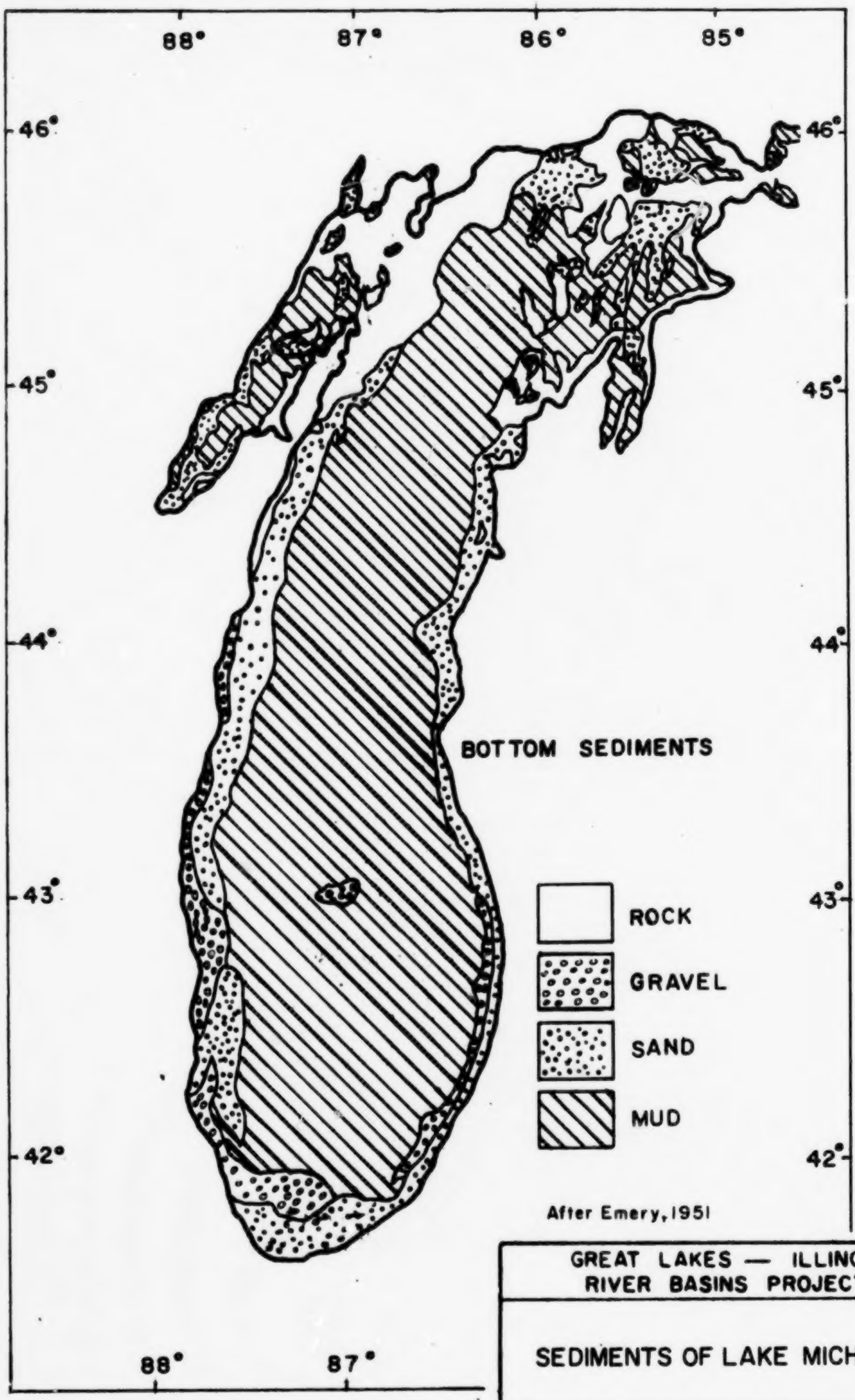
US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 2-2


STRAITS AREA
GREEN BAY
30
60
90
120
150
180
210
240
270
NORTH
DIVIDE
SOUTH
LEGEND
CONTOUR IN METERS
270
240
210
180
150
120
90
60
30
Area of Complex Bathymetry
Percent of Area
20
40
60
80
100
Depth (m)
0
60
120
180
240
300
Sea Level
0 16 32 48 Km.
Scale
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT
LAKE MICHIGAN
BATHYMETRIC CHART
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region
Chicago, Illinois

After Emery, 1951

FIGURE 2-3


88°
87°
86°
85°
46°
45°
44°
43°
42°
BOTTOM SEDIMENTS
ROCK
GRAVEL
SAND
MUD
88°
87°

After Emery, 1951

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SEDIMENTS OF LAKE MICHIGAN

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 2-4

Physiography and Sediments

Lake Michigan can be divided into five areas having different physiographic characteristics. However, for water quality purposes the Divide Area is not classified separately. These areas are termed South Basin, Divide, North Basin, Straits Area, and Green Bay (Fig. 2-3).

The South Basin extends from the southern tip of the Lake to a line connecting Milwaukee and Grand Haven. This area has gentle topography, suggesting excavation of a thick homogeneous formation, followed by silting caused by glacial outwash. The bottom materials consist of sand along the shore and on the beaches, gravel largely at water depths between 15 and 30 m, and mud in deeper water. Hough (40) ascribes this distribution to the winnowing of glacial till by wave action, whereby gravel is a lag deposit, sand is carried landward to the shore, and mud remains in suspension until it reaches the quiet water of the Lake bottom.

The next physiographic area is the Divide, which consists of two separate ridges. According to Thwaites (77), 1947, the southern ridge marks the position of the resistant Traverse limestone and the northern one the resistant Dundee limestone. These ridges may also consist in part of recessional moraines. Bottom notations on various charts show the presence of boulders and clay near the west shore, probably indicating glacial till. Sand forms a belt between water depths of about 15 and 90 m on the west side and from shore to 38 m on the east side. The few bottom notations in the middle of the section show mud almost exclusively. Most likely, the tops of the ridges consist of coarser material.

The third area, the North Basin, extends north from a line between Manitowoc and Manistee to a line between Frankfort and Manistique. It consists of one main basin which, unlike the South Basin, is irregular in shape. The topography is suggestive of excavation of a thick nonhomogeneous rock with only slight mantling by later sediment. The maximum lake depth is found in this basin. This section appears most likely to have been excavated by glacial erosion. Along both shores is a belt of rock that, on the west side, ranges in width up to about 24 km. Gravel is probably common in the rock area. A belt of sand of varying width borders the rock. In deep water, chart notations show mud exclusively. In each of the three physiographic sections which comprise the main area of the lake, coarser sediments are better represented on the east shore.

The fourth area, the Straits Area, is one of very irregular topography, accounted for by the presence of alternating belts of hard and soft rocks that were oriented perpendicular to the movement of the glaciers. The deep depressions and rocky ridges are similar to the glacial erosional topography found in the fiord coasts of Norway.

In the Straits Area is the outlet of Lake Michigan. Although the narrowest point is in the Straits of Mackinac, the shallowest divide is located 72 km westward, well within the wider part of the Lake. Between these two points, and extending eastward into Lake Huron, is a narrow canyon, approximately 8 km wide and 39 m deep. The complexity of the bottom contours is matched by the variety of the bottom materials. Figure 2-4 shows that rock occurs around the shores of all islands and at the tops of submerged hills. Sand is abundant only in three large areas near the extreme end of the lake. Mud occupies the depressions and lower areas.

The Green Bay Area is fairly shallow, averaging about 24 m with a maximum of 50 m near one of the entrances. The north end of the Green Bay section is exposed to the waves of Lake Michigan and, as a result, its floor consists principally of rock. Within the area of quiet water at the south end of Green Bay, the sediments have a more normal distribution, with rock along the shore, sand generally paralleling the rock, and mud farthest offshore.

Hydrology

The water balance for Lake Michigan can most easily be determined by the water budget. Table 2-1 lists all the gaged tributary streams into Lake Michigan. The total inflow as estimated by the USGS (79), averaged from the total gaged and ungaged stream basins, is 1,102 m^3 per second (38,900 cfs). Table 2-2 lists the essential factors in the water budget and shows that the computed outflow at the Straits of Mackinac is about 1,134 m^3 per second (40,000 cfs).

The extent of ground water exchange is not known, but is considered as minor in the computations.

The above figures could be checked by adding the Lake Huron inputs plus the inflow at the St. Marys River and figuring the balance at the Detroit River. The difference should approximate the Lake Michigan contribution.

Using figures for precipitation and evaporation by Ownbey and Willeke (59) and inflow figures for the Michigan-Huron Basin, the differences are considerable. Bergstrom and Hanson (8) report that the combined tributary inflow for the two basins is 2,073 m^3/sec (73,200 cfs). Assuming the Lake Michigan inflow figures are valid (1,101 m^3/sec), the Lake Huron tributary inflow can be estimated at 972 m^3/sec (34,300 cfs). Precipitation minus evaporation is estimated at 472

TABLE 2-1

TRIBUTARY INFLOWS*

RIVER	AVERAGE FLOW CFS	AVERAGE FLOW M³/SEC	GAGED AREA SQ MI	GAGED AREA SQ KM	YEARS OF RECORD
Michigan					
Boardman	186	5.3	223	577.6	13
Little Manistee	162	4.6	200	518.0	9
Manistee	1,933	54.7	1,780	4,610.2	14
Big Sable	137	3.9	127	310.8	23
Pere Marquette	608	17.2	709	1,836.3	26
White	367	10.4	380	984.2	8
Muskegon	1,889	53.5	2,350	6,086.5	43
Grand	3,362	95.2	4,900	12,690.0	39
Black	45.2	1.3	65.8	170.4	5
Kalamazoo	1,269	35.9	1,600	4,144.0	35
Paw Paw	373	10.6	390	1,010.1	14
St. Joseph	3,025	85.7	3,666	9,494.9	35
Menominee	3,098	87.7	3,790	9,816.1	53
Ford	324	9.2	450	1,165.5	11
Escanaba	895	25.3	870	2,253.3	24
Indian	369	10.4	302	782.2	27
Black	25.1	0.7	28	72.5	14
Wisconsin					
Peshtigo	832	23.6	1,124	2,911.2	12
Oconto	569	16.1	678	1,756.0	54
Fox	4,140	117.2	6,150	15,928.5	69
Milwaukee	381	10.8	686	1,776.7	51
Cedar Creek	62.3	1.8	121	313.4	35
Indiana					
Burns Ditch	127	3.6	160	414.4	17
Totals	24,205.6	684.7	30,749.8	79,622.8	

*USGS (79)

TABLE 2-2

WATER BUDGET FOR LAKE MICHIGAN

	AVERAGE FLOW (1)		AVERAGE FLOW (2)	
	M^3/SEC	CFS	M^3/SEC	CFS
Positive Contribution				
Tributary Inflow(3)	1,104	39,000	1,101	38,900
Precipitation	1,374	48,500	1,466	51,750
Ground Water	---	---	11	400
	2,478	87,500		
Negative				
Evaporation	1,286	45,400	994	35,100
Diversion (1940-1960 avg)	92	3,240	92	3,240
	1,378	48,640		
Net Outflow	1,100	38,860	1,492	52,710

(1) Precipitation and evaporation from Ownbey and Willeke (59).
(2) Precipitation, evaporation, and groundwater from Bergstrom and Hanson (8), estimated at one-half the Michigan-Huron total.
(3) Includes ungaged tributary inflow.

m^3/sec and the St. Marys River inflow (66 year average, USLS) is 2,079 m^3/sec (73,400 cfs). The St. Clair River outflow from Lake Huron (66 year average, USLS) is 4,993 m^3/sec (176,300 cfs). The resulting outflow for Lake Michigan is computed at 1,470 m^3/sec (51,906 cfs). Obviously the precipitation-evaporation figures are the greatest sources of error in the computations, and this problem is far from resolved today. The conservative figures of Ownbey and Willeke (59) were used in most of the Lake Michigan calculations for the remainder of the report.

Lake Levels

Lakes Michigan-Huron are considered hydraulically as one lake. The reference datum for Lakes Michigan-Huron water surface, referred to as "Low Water Datum," is 576.80 feet (175.81 m) above sea level on the International Great Lakes Datum of 1955. The lowest monthly mean levels during the past 105 years have occurred in the past few years, being 0.42 m below the datum in March 1964. The highest levels occurred in June 1886 when the water was 1.56 m above the datum. The extreme range is 1.98 m, or the greatest of all the Great Lakes ranges. While no doubt the prevailing drought conditions contributed to the extreme lowering of the Michigan-Huron Basin in 1964, during the same period neither Lake Erie nor Lake Ontario experienced a similar drop in level, even though the drought conditions were very similar in their drainage basins. It is probable that changes made by man in the outlet channels have contributed to the extreme range in the Michigan-Huron water levels; the flow from Lake Superior is regulated by controlling locks on the St. Marys River and is not subject to changes in the connecting channels.

In addition to the long-term variations, which reflect changes in storage volume, Lake Michigan has tides (lunar and solar), seiches, and surges. These short period fluctuations do not result in a change in volume, but a change in the water level shape. In general, tides are minor, 7.2 mm lunar and 3.1 to 6.3 mm solar (Hutchinson, 44). The seiches rarely exceed 0.3 m in height. The first five seiche periods, of the longitudinal seiche, are shown in Table 2-3 (Rockwell, 67).

In a spectral study of surface level fluctuations, Mortimer (55) interpreted dominant spectral peaks at approximately 9.0, 5.2, 3.7, 3.1, and 2.5 hours as corresponding to the first five longitudinal modes and demonstrated a striking transverse first-mode seiche at 2.2 hours in the southern half of the Lake. In addition, he demonstrated resonance in Green Bay between the free period of oscillation of the Bay, at approximately 11 hours, with the lunar tide 12.4 hours and the first Lake Michigan mode at 9.0 hours.

TABLE 2-3

COMPUTED PERIODS OF THE FIRST FIVE MODES

MODE	HOURS
1	8.83
2	4.87
3	3.54
4	2.86
5	2.39
0	47.8 (Lakes Michigan-Huron)

The interlake seiche, 47.8 hours, has been observed at 50 and 51 hours with current meters and in a spectral analysis of the speed data.

The surge in Lake Michigan is unusual because of its suddeness and its height. Waves of nearly 2 m have been observed and reported since the surge of 1954 which took the lives of seven people in Chicago. Hughes (41) reports on the operational basis for prediction in Lake Michigan and an explanation of the wave. The wave is one which was reflected back from the eastern side of the Lake and increases in height due to the shallowing water. A pressure jump and perhaps the accompanying winds produce the original wave. The maximum transfer of energy from wind to water appears to occur when the pressure jump associated with squall lines happens to be traveling at the speed of the free wave in water, which is a function of the square root of the depth (Donn and Ewing, 28).

CHAPTER 3

INTRODUCTION TO LAKE CURRENT STUDIES

The study of currents in Lake Michigan reported herein is part of the overall program of investigations undertaken by the Great Lakes-Illinois River Basins Project. The ultimate objectives of the studies are: to assist in predicting the fate of pollutants introduced into the Lake; to assess the effects of waste inputs on lake water quality--effects both local and area-wide, both now and in the future; and to aid in the making of wise decisions for protecting this valuable water resource.

Waste-bearing waters are dispersed from a point of input to the Lake by some combination of three processes: molecular diffusion, turbulent mixing, and mass transport. The relative importance of each process depends on physical conditions in the Lake. For example, in completely quiescent waters the predominant process would be molecular diffusion. Turbulence (the existence of randomly-varied water velocities) in the vicinity of the point of input will greatly accelerate the rate of dispersal over that effected by molecular activity alone. If, superimposed on this random turbulence, there is a prevailing velocity, then the water mass as a whole, and the accompanying waste waters, will move in that direction. Knowledge of the existence (or absence) of such movements is essential, both for predicting the fate of pollutants and for planning strategic locations of waste input and water extraction points to minimize short-circuiting.

The objectives of the Lake Michigan current study are, then: to determine the variations in physical characteristics, temperature and density, of water within the Lake; to measure the water movement patterns over a period of time; and to develop, from considerations of cause and effect, a theoretical basis for generalizing the observed conditions.

General Considerations

To comprehend the details of the data on currents it is logical to review the theoretical concepts and the terminology of the study.

A pollutant which is a liquid or a suspension of small particles, when introduced into a body of water, may be diffused (molecular scale), mixed or diluted (larger scale), and advected or moved by currents (still larger scale). All three scales of motion are present in Lake Michigan. Each will be discussed in turn and its significance considered. It will be evident by the end of the discussion that there are gaps in our knowledge of these various scales. Some of these gaps have been filled by field investigations; the rest await advances in theory and instrumentation.

Diffusion

Molecular diffusion is a complex random motion directly associated with molecular motion and accelerated by the thermal agitation of individual molecules. It is perhaps the least important motion for pollutants in Lake Michigan in comparison with the effects of larger-scale movements. Other than acknowledging its existence, molecular diffusion will not be considered further.

Turbulent Mixing

Turbulent mixing is a complex random motion not directly associated with the agitation of individual molecules. According to Corrsin (21) "...turbulence can be expected in a fluid whenever there is a shearing flow and the inertial effects are much larger than viscous effects." These conditions are often satisfied in Lake Michigan. Turbulence affects the dispersal rate of pollutants much more than does molecular diffusion.

Generally speaking, "...much of the core of the turbulence problem has yet to yield to formal theoretical attack" (Corrsin, 21). Mathematical difficulties in handling nonlinear expressions have greatly hampered progress; the nonlinearity implies that there are no simple relationships readily susceptible to mathematical treatment. Work relating to natural waters, both salt and fresh, has been published by Richardson and Stommel (64), Stommel (74), Joseph and Sendner (46), Noble (56), and others. In addition, there is significant unpublished work by Schonfeld of the Netherlands, Okubo of the Johns Hopkins University's Chesapeake Bay Institute, and others. Recent researches into flow in stratified fluids are directly relevant to the Lake Michigan problem, and these have been reviewed by Mortimer (54). A good deal of research is now being carried out in this field, so long neglected in comparison with turbulence in homogeneous fluids, and theoretical and experimental progress is being made.

The wind, acting both directly and indirectly, appears to be the chief force causing water motion in Lake Michigan, overcoming inertia and stability and resulting in internal turbulence. Wind stress on the water surface can cause waves, set-up, and currents, and if abruptly terminated after a sufficiently long period, may result in a seiche.

If water temperatures are vertically isothermal, the wind can stir the whole Lake. Wind results in waves and orbital particle motion to depths of at least half a wave length if thermal stratification is not too strong. If the wind blows from the same direction for a few hours, it will cause set-up; that is, wind stress will drag surface water to the leeward side of the Lake, causing a measurable piling up of water against the shore. Mixing will occur while water is moving toward the shore and while part of the piled-up water is escaping by moving parallel to the shore or by reverse flow as a subsurface current. In addition, when the wind either stops blowing or shifts direction, the piled-up water begins to move toward the opposite side of the Lake. Often it surges back and forth across the Lake several times with a period determined by basin geometry and fluid density; this is called a surface seiche. The seiche results in further, though less important, mixing. If there is significant density stratification, an internal seiche may also be started. The internal seiche, like the surface seiche, is a wave form at a density interface, though in this instance there is water above and below, while for the surface seiche air is above and water below. Periods of internal seiches may be longer and the amplitudes greater than surface seiches. Because of the large amplitudes, internal seiches can accomplish more mixing at stable thermocline depths - generally in excess of 22 m. Seiches may be uni- or multinodal. The possibility of their presence makes a single temperature observation suspect; observations should be repeated at each location to ascertain conditions. Observations off Chicago by Project personnel in October 1961, indicated 8-m vertical movement of an isotherm within 3 1/2 hours. If such motion is typical, attempts to estimate the volume of water available for mixing in the epilimnion (or upper layer) without a set of simultaneous temperature-depth measurements could be disastrously in error.

It is pertinent to insert a discussion of the Lake Michigan temperature structure here, because temperature structure determines density structure, which in turn determines stability. The most important published works are by Van Oosten (84), describing data from 136 stations occupied from mid-April to mid-November in the years 1930, 1931, and 1932; by Church (20), describing 2,000 bathythermograph soundings made between November 1941 and February 1944; by Ayers et al., (2), describing four synoptic studies of 50 or more temperature stations occupied in June and August 1958; and by Mortimer (54) giving the first detailed picture of temperature distribution in a cross section (his figure 6), with a presentation of evidence of inshore upwelling and wavelike changes in temperature provided by waterworks intake records, and a prediction of the nature of the internal waves involved.

During early winter months the Lake surface cools and convective mixing occurs as the denser colder water sinks. This mixing may not affect the deeper areas of the Lake where water may already be at maximum density. At some time during this period the entire Lake will reach a condition of maximum density, about 4°C. At this time vertical convective mixing ceases. As the surface temperature continues to drop, the less dense colder water remains at the surface except for such mixing as may result from wind or wave action. Following the winter season, the temperature increases slowly until late spring, when the whole Lake again reaches the temperature of maximum density. During this latter period most of the Lake is again convectively mixed. Following the spring period when the Lake is vertically isothermal at temperatures somewhat higher than 4°C, the surface temperatures will increase rapidly until early August, by which time a very stable stratification has developed, starting with the formation of a thermocline (a layer of rapid temperature decrease 3 to 15 m thick). Thermocline formation occurs first in the shallow inshore waters, and it is at this time, when the central part of the Lake is isothermal at near 4°C, that the thermal bar described by Rodgers (68) may form. Ultimately, however, the result of spring warming is to produce a homogeneous surface layer over the whole of the Lake, with temperatures in the region of 18° to 22°C separated by a thermocline (Church, 20 and Ayers, 2) from bottom water which maintains a temperature close to 4°C. During the time of intense stratification (greater temperature differential within the thermocline), it is unlikely that even the strongest winds could cause complete vertical mixing; only the water above the thermocline (the epilimnion) is available for thorough mixing with pollutants. Cooling of the epilimnion begins with September storms, and the thermocline weakens as the surface homogeneous layers cool and increase in depth until the whole Lake becomes isothermal at about 4° to 5°C in December.

According to Church (20), minimum surface temperatures (between 0.5° and 4.0°C) are reached between the middle and end of March, at which time the main body of the Lake is vertically isothermal. These temperatures are lower than those producing maximum density; if such low temperatures could be found in the deepest part of the Lake, then their presence would conclusively demonstrate complete vertical mixing of the entire Lake volume for the year (Birge, 9). (Church found them in much shallower water on the rise between Milwaukee, Wisconsin and Muskegon, Michigan.)

Dissolved oxygen (DO) enters the water mainly from the atmosphere. During periods of overturn the DO will tend to approach saturation values, but during periods of stratification DO losses below the thermocline will not be restored by vertical mixing. If pollutants with sufficient Biochemical Oxygen Demand were introduced into or below the thermocline, the DO concentration might drop rapidly to low levels.

Two points should be emphasized. First, the volume of water available for mixing keeps changing throughout the year, and it is not known whether the entire Lake volume mixes completely. Thus, at certain seasons of a year, only the uppermost water (15 m) may be available for diluting pollutants, although events near shore, where the pollutants enter, may often be complicated by the upwelling and downwelling phenomena described by Mortimer (54). Second, there is a stable density stratification for a significant portion of the year establishing three zones, each having its own temperature and density characteristics. Accordingly, the density of any pollutant introduced into the Lake determines whether the pollutant would stay on the bottom, at intermediate depths, or rise to the surface.

Advection

Mixing as accomplished by turbulent motion results from complex random movements involving relatively little transport of a water parcel, but changes in its internal distribution. Advection is roughly the opposite of turbulent mixing, and refers to linear movement or gross motion of a water parcel with mixing along its boundaries. There are a number of possible situations between the two extremes, random turbulence and prevailing advection.

Advection theory, in part, is in a more advanced state than turbulence theory; however, a situation often is so complex that it is exceedingly difficult to obtain even semiquantitative predictions, especially in the vicinity of shore lines (Hutchinson, 44).

In Lake Michigan the wind and pressure fields seem to be the chief causes of advection (as well as internal turbulence, previously discussed). Tides are negligible for most purposes, having a range of some 1 cm (Judson, 47). Seiches are important to advection only in restricted areas, such as the Straits of Mackinac, and perhaps in the entry channels to Green Bay. Precipitation minus evaporation, although not known in definite detail, is small enough to be neglected in this instance. Because of the large area of transverse cross section of the Lake, net flowthrough produces negligible velocities of advection; however, flow in the Straits of Mackinac is often reversed by seiches and wind-tilt. Church (20) noted that during most of the year denser water was in the center of Lake Michigan and less dense water at the edges, implying a slow counterclockwise density circulation superimposed on the net flowthrough. Project personnel found a similar distribution off Chicago in the fall of 1962. A careful review of the data indicates the presence of more than one circulation pattern. This is supported by differences in earlier studies by Harrington (36), Johnson (45), and the four synoptic cruises by Ayers (2). According to Ayers, major current changes caused by the wind are often superimposed on the more stable, slower flow, and changing winds are responsible for the varying currents observed.

Haines and Bryson (35) find that the speed of a surface current is 1.3 percent of that of the wind producing it, provided the wind speed is less than 5.9 m/sec (13 mph); above this critical speed, the relationship is believed to be nonlinear. Shulman and Bryson (72) find the direction of surface transport is about 20.6° to the right of the wind direction and that the "depth of frictional influence" is between 1.8 and 3.3 m. These studies were conducted on Lake Mendota at Madison, Wisconsin and may not be entirely applicable to Lake Michigan.

In the discussion of thermal structure it was pointed out that the thermocline separated the homogeneous less-dense epilimnion from the denser homogeneous bottom water. Bryson and Bunge (15) find that when the wind suddenly drops or shifts direction after set-up is established, a rapid increase in current velocity is observed just above the thermocline. They consider this current to be the first swing of an internal seiche. Accordingly, significant currents may exist both at the top and bottom of the epilimnion. Lathbury, et al., (49) found significant currents below the thermocline also, which they consider attributable not to seiches but to thermally-and/or wind-induced pressure gradients. Set-up causes a hydrodynamic pressure gradient, resulting in currents along or perpendicular to the shore. Shoreline and bottom topography will also influence currents. Because of the multiple forces to be considered, attempts to predict currents soon become complicated.

Recent studies have shown that currents exist through the entire vertical column of water. Current velocities over 50 cm/sec at a depth of 30 m were measured by the Project.

On one occasion Project personnel found floating pollutants in the vicinity of Chicago's beaches and water intakes, for several consecutive days (USPHS, 82). Generally speaking, surface currents are weak and southbound near Lake Michigan's west shore, but narrower, stronger, and northbound near its east shore. Sometimes there is evidence of a counterclockwise eddy in the Lake's southern basin. Again, it is emphasized that these conditions are variable.

Meteorology

The winds, precipitation, and evaporation over Lake Michigan have rarely been measured. One study "Report on Wind Velocities at the Lake Crib and at Chicago" by Hazen (37) (1883) was one of the few works undertaken to determine the wind differential that exists between the land and the lake. Major Ira Hunt (43) U. S. Lake Survey, working on Lake Erie, made some calculations on the wind differential that exists over the Lake. Applying the results of this study to Lake Michigan it would appear that winds over Lake Michigan can be 96 percent greater than those over the City of Chicago at certain times of the year.

Data on evaporation and precipitation over the Lake surface are limited to estimates by the U.S. Lake Survey rather than precise observations. Radar studies of precipitation variations over the Great Lakes are still in the experimental stage by both the United States and Canadian Weather Bureaus. Verber (87) reports that convectional-type rainfall over Lake Erie is less than at adjacent land stations. The U.S. Lake Survey embarked on a similar study in northern Lake Michigan, and the results were reported by Bloust (11). Estimates on evaporation have varied from 53 to more than 76 cm per year. Estimates on precipitation have also varied in the same range. The U. S. Lake Survey (81) states that the average annual precipitation over Lake Michigan (1900-1960) is 77 cm.

Possible Fate of Pollutants

The following factors influence the fate of an effluent discharged into Lake Michigan: (a) Existing current regime; (b) Winds; (c) Bottom topography; (d) the Earth's rotation; and (e) Density difference between pollutant and Lake water.

If there is a current regime, it will transport any pollutants introduced into it. As previously noted, there may be a counterclockwise gyre in the entire Lake or an eddy in the southern portion that would be the prevailing circulation feature.

Wind-induced currents can move Lake pollutants. The wind currents may be superimposed on any previously existing currents and can move in any direction.

Topography may determine whether a pollutant remains in an area or not. If the pollutant is less dense than Lake water, then it may be moved by wind currents until it is trapped against a shore. If the pollutant is denser than Lake water, it may run along the bottom and collect in depressions.

If an effluent is discharged into the southern basin of Lake Michigan and there is a density difference between the effluent and the Lake water the following situations are possible:

1) If the effluent is low density, it will rise to the surface and under certain wind conditions may be carried along the southern and western shores, possibly affecting adversely water supplies that serve populations totaling several million people as well as heavily used bathing beaches. Such conditions could last for many days.

2) If the effluent is soluble, it may be kept in the southern end of the Lake by the eddy which is sometimes there. Under such condi-

tions, concentrations of chemical constituents well in excess of those normally present may build up.

3) If the effluent is discharged at the bottom and has the same density as the Lake water, there will be little vertical movement. Under certain wind conditions it may be carried by subsurface currents to the Chicago water intakes or bathing beaches with little opportunity for dispersion or dilution, or brought to the surface by upwelling.

Each of the three possible situations cited above will be considerably more serious if it follows a period of low wind and water currents during which effluent concentration may build up in the vicinity of diffusers. Such conditions may occur even when no ice is present and, on the basis of existing wind records, may be expected most frequently during summer months.

4) If the effluent is of high density, it will sink to the bottom and may run down to and collect in the southern basin. Concentrations of various constituents may build up and seriously interfere with existing aquatic life. The density of treated effluent is so close to that of the Lake water, that, at different times of year, temperature changes in the Lake may result in the occurrence of any of the possibilities listed above.

Previous Studies

A detailed literature search disclosed three important studies pertinent to the measurement of currents in Lake Michigan. In the years from 1892 through 1894, Mark Harrington of the U. S. Weather Bureau released over 1,500 drift bottles in the Lake, of which only about 203 were recovered during the 3-year period (36). These returns formed the basis of the first map of Lake Michigan surface currents. In 1954-55, James Johnson of the U. S. Bureau of Fisheries (45) completed an intensive study of surface currents using drift bottles and drift envelopes. Out of 6,260 releases, some 2,870 were recovered during this study. The study results indicated that during 1954 no stable pattern of surface currents existed. In general, Johnson found the drift was from west to east and the north-south movements were about equal. A similar pattern existed in 1955 except that the drift in the eastern areas was mainly to the north. In 1958, Ayers and others, (2) published the results of a series of synoptic surveys, in which they applied a modification of the dynamic height method and published the first map of Lake Michigan showing subsurface water movement. The method, however, is open to question because of the choice of boundary conditions (Ayers, 1).

Townsend (78), took sharp issue with Harrington on the method of presentation of data. He stated that in such a confined area as Lake

Michigan, Harrington could not assume curved line motion but should have used straight line motion. Townsend's ideas were partially verified by studies on Lake Erie (Verber, 85).

It is difficult to translate drift card or bottle movements over many days into those of actual currents. The only positive statement that can be made about drift methods is in reference to the points of release and retrieval. Such movements at best can only demonstrate a type of pattern between the times of release and recovery. The seemingly random changes between Ayers' and Johnson's work graphically illustrate this point. The more recent studies using bottles and cards did not claim to show anything other than the conditions that existed at that time and place. Harrington, however, tried to pin down specific current patterns from far less data over a much greater time span. The meters which exist today were unknown ten years ago and earlier scientists could only use the tools then available.

The dynamic height method of obtaining subsurface current data has not been substantiated by means of current meters. Criticism of the method is based on two assumptions. One, the method assumes a zero velocity depth level which may or may not be correct. Two, the theory assumes constancy in the isothermal lines over a short period of time, whereas it is known that internal waves may produce very striking thermal changes in lakes and also in the ocean (Verber, 86).

Since none of the past studies showed net circulation, maximum current speeds, effects of storms, or detailed inshore circulation, further work was necessary to give the answers needed today.

Procedures

Procedures for the study are a combination of old and new techniques. These have been selected through consultation with oceanographers of the Chesapeake Bay Institute, Harvard University, and New York University.

The study period on the Lake involved approximately 1½ years of data collection. The review of past studies, experimental testing of equipment, purchase of equipment, and the development of techniques preceded the actual study and required nearly 18 months.

To provide quality control of the data, services were secured from other agencies. The Project established cooperative arrangements with the National Oceanographic Instrumentation Center for basic calibration of the instrumentation. Aircraft and photographic techniques used in the study of littoral currents were provided by personnel of the U. S. Naval Air Station at Glenview, Illinois. The precision of navigation was accomplished through utilization of vessels and personnel of the U. S. Corps of Engineers and private facilities.

Temperature Studies

Temperature studies on Lake Michigan were made from September 1961 to 1964. Approximately 20 cruises were made on the Lake during this period, with more than 1,300 bathythermograph casts. Information gained during these studies was used to establish the various configurations of the thermocline during spring, summer, fall, and winter. Temperature information gained throughout the year was used to determine the depth of mixing and variations in density layers within the Lake.

In addition to securing data from bathythermographs the Project secured 200 temperature recorders, designed by Woods Hole Oceanographic Institute, which were used in conjunction with the current meters to determine the location of the thermocline and magnitude of internal waves.

Tracer Methods

Drogues were used for inshore studies. The drogues consisted of a cloth or metal vane suspended in the water at the desired depth by a line attached to a small surface float. The cross section of the vane is sufficiently large to make the movement of the assembly dependent on forces acting directly upon the vane, with negligible effects from forces acting on the line and surface float. The movement of the vane below the water surface is followed by corresponding movement of the surface float. Several drogue studies, using both a small boat and aerial photography, were conducted in the Chicago area during the study period. The first drogue studies made by the Project were used to develop techniques and methods of study. Drogues were used to study current patterns and mixing in shallow water.

Fixed-Position Current Metering

Of the available techniques for the investigation of currents, the use of fixed stations with automatic recording meters was selected as most applicable for studies of mass water movements in the Great Lakes.

Three types of measuring systems were considered seriously by the FWPCA: The Woods Hole Oceanographic Institution meter, developed by Dr. William S. Richardson (65), a telemetry system devised in 1962 by the U. S. Corps of Engineers (80), for the Public Health Service; and a modular system, Frantz (33), devised by Marine Advisers, Inc. The first is completely self-contained and has an automatic mechanical system for recording data on 16 mm photographic film. The other two are dependent upon an external unit to supply power and record data electronically. All have many desirable features not found in other types of current meters, such as:

1) The ability to measure low current speeds, down to about 1.0 cm (0.03 feet) per second by utilizing a Savonius rotor.

2) The ability to operate untended for up to four months while recording observations hourly.

3) The ability to measure direction ± 7°.

4) The ability to record observations at shorter intervals than one hour.

Each meter has particular characteristics which make it desirable for use under certain conditions. After a careful review of the three meter systems as they related to study requirements, the Woods Hole meter was selected as the most suitable for anticipated field conditions.

After the method of study was selected and testing of meters was underway, plans were developed for selecting the number of stations to be instrumented, their location, instrument servicing, and the processing of data. The selection of stations and the number of meters per station were subjects of a conference held in Chicago with scientists from the Great Lakes States and Canada. It was decided that the standard procedure of equal area and depth coverage was the most logical method. To study all of Lake Michigan it was agreed that between 30 and 40 stations should be set. The number of meters to be set posed a problem because of the variability of the thermocline. It was readily agreed that the meters should be set at fixed depths, and at closer spacing in the upper layers. The depths selected were: 10, 15, 22, 30 m and each succeeding 30-m level. No meter was set less than 10 m below the surface because of problems resulting from surface waves.

The preliminary recording of data was different for the various types of meters. The telemetering station recordered hourly on its internal recording system and transmitted the data every 4 hours by radio to a receiving station. The telemetry system reported total revolutions of the Savonius rotor in each 4-hour interval together with one instantaneous direction reading made at the time of reporting. The Woods Hole meter at different times was used on a continuous recording mode and then on a mode recording 50 seconds continuously once every 20 minutes. The recording for the full-scale study was set at a continuous 50-second recording period once each 30 minutes for the winter months, but intervals were reduced to 20 minutes for the rest of the year. The longer period was adopted for winter operation to provide a margin of safety against exhaustion of the power supply batteries inside each unit. During severe winter weather it was impractical to visit the stations for retrieving data, replacing batteries, and other servicing. Approximately 200 Woods Hole current meters were used in the study.

Equipment Testing

Many of the theoretical concepts of water movements in the oceans and the Great Lakes have defied testing because of the lack of adequate instrumentation. With the advent of the Savonius rotor and the development of the Woods Hole meter a valuable new tool was made available to the scientist. An equally important development and essential to the mass use of the meter was the perfection of an automatic readout system in July 1962. Reading speed and direction every 20 minutes, each of the 200 meters would record 52,560 observations a year. The manual reading of this information directly from film would have been prohibitive in cost.

Description of Test Studies

The study of currents in Lake Michigan by using current meters began October 21, 1961 with the setting of an experimental telemetry station. The station was first set about 40 km northeast of Chicago (Figure 3-1), but was removed after three days because of a defect. It was reset on May 15, 1962 about 24 km northeast of Chicago. From May 15 through November 1, 1962, several different types of station were set for the purpose of evaluating meter performance, mooring systems, and other features of the instrumentation, preliminary to the full scale study.

Results of Test Studies

This section will describe the results of the observations with respect to the following factors:

1) The reliability and sensitivity of instruments under field conditions.

2) Mooring characteristics.

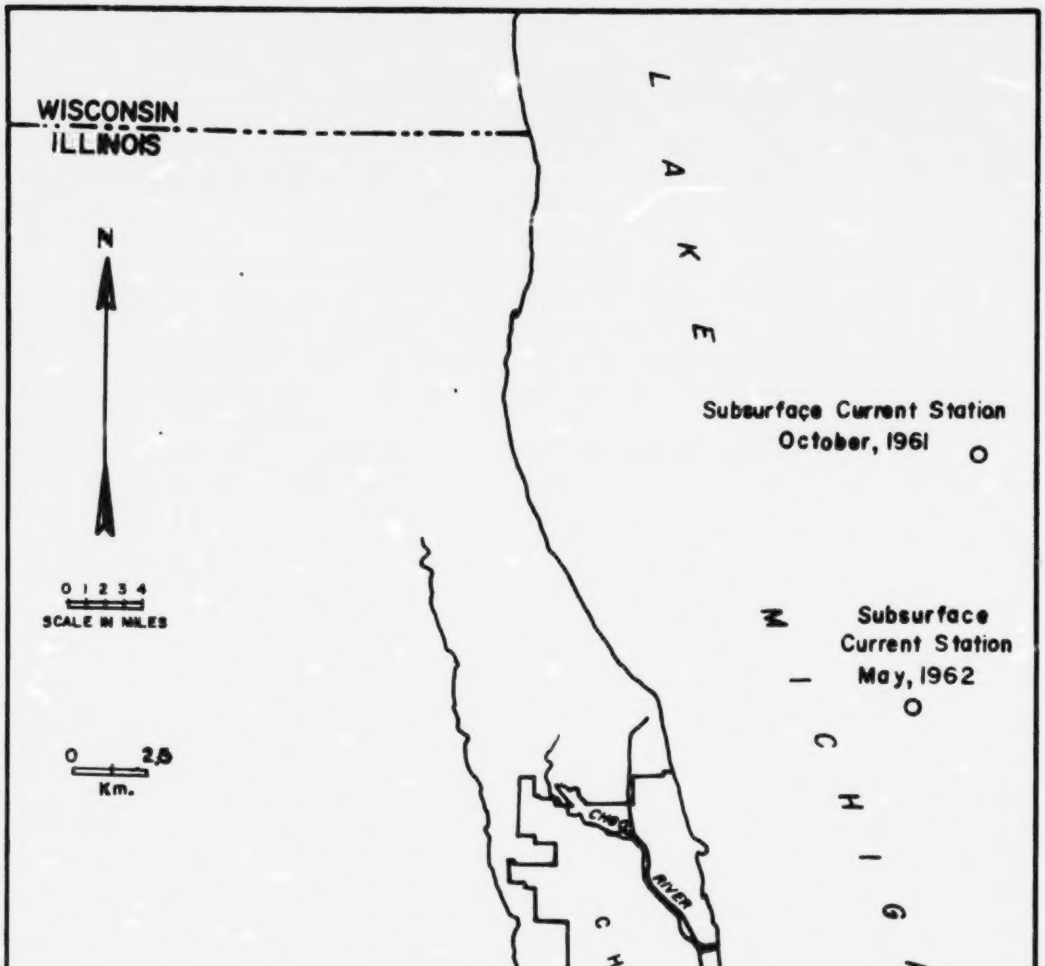
3) The operating characteristics of different types of current meter installations.

4) Flow characteristics.

5) The relationships between winds-on-shore and lake currents.

6) Correlation between meters at one station.

The results of the tests are shown on a series of graphs. These graphs present results of statistical tests on the data obtained from the current meters. Speed readings are given in centimeters per second.


WISCONSIN
ILLINOIS
N
0 1 2 3 4
SCALE IN MILES
0 2.5
Km.
LAKE MICHIGAN
Subsurface Current Station
October, 1961
Subsurface
Current Station
May, 1962
CHICAGO
CHGO. RIVER
SANITARY & SHIP CANAL
RIVER
CALUMET SAG
DES PLAINES
DU PAGE R

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

CURRENT METER STATIONS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 3-1

Direction readings are given in terms of degrees clockwise from magnetic north. The readings for direction given in this section represent the direction from which the current is coming.

Figures 3-2 and 3-6 were examined for correlation and equality in direction. If the absolute value of the median difference of the readings between two meters is significantly less than 90° a positive correlation exists.

Reliability

The reliability and sensitivity of the meters were determined by an examination of results, i.e., speed and direction data, rather than by an analysis of the physical characteristics of the meters. A study of the data alone will not disclose systematic errors in the measurements; however, such errors are believed to be small, based on tank tests in which the sensors were towed through still water.

The data used for reliability evaluation were from two separate stations - the telemetry station with three meters, set at 18, 27, and 36 m, and a station with one meter of the Woods Hole type set at 40 m. The two stations were within 90 m of each other. The recording interval for the telemetry station was once every four hours with some observations at 10-minute intervals. The total time of recording was 63 days. The Woods Hole meter recorded continuously and the data were printed out at 1.25-minute intervals. The record length for this meter was 6 days, July 5 to 10, 1962.

Figure 3-4 shows a series of current meter readings taken during a period of increasing flow. The data show two types of changes in the speed, a long-period systematic rise and a short-term random fluctuation. The long-period rise shows an increasing current speed. The short-term random fluctuation could be due to changes in the current speed or to instrumental error. At this time it is not possible to distinguish between the two changes and they are grouped together and treated as physical measurement limitations. The amount of the random fluctuations is used to estimate the precision (repeatability or consistency) of the data.

The problem of variation measurement is to measure the short-term changes without including the long-term systematic variation. The simplest solution to this problem is to assume that the long-term systematic variation is approximately zero over a short period of time. Thus, over a short period of time, the total variation can be used to approximate the random fluctuation.

Under steady-state conditions, the larger the quantity of data collected, the more accurately it will represent the data of which it is a sample. However, the larger the quantity of data used, the greater the time span. Thus, the problem is to use a large quantity of data without spanning a long period of time. The solution is to have as short a period of time between observations as possible.

The data in Figure 3-4 from the Woods Hole meter were plotted from the readings made at 5-minute intervals. The figure is a plot of magnitude (speed) against time. The plot represents a 12-hour portion of a 40-hour period and indicates that the meter is capable of detecting long-term systematic changes in speed. However, initial tests showed a large random variation in direction at higher speeds, due to the type of mooring system used.

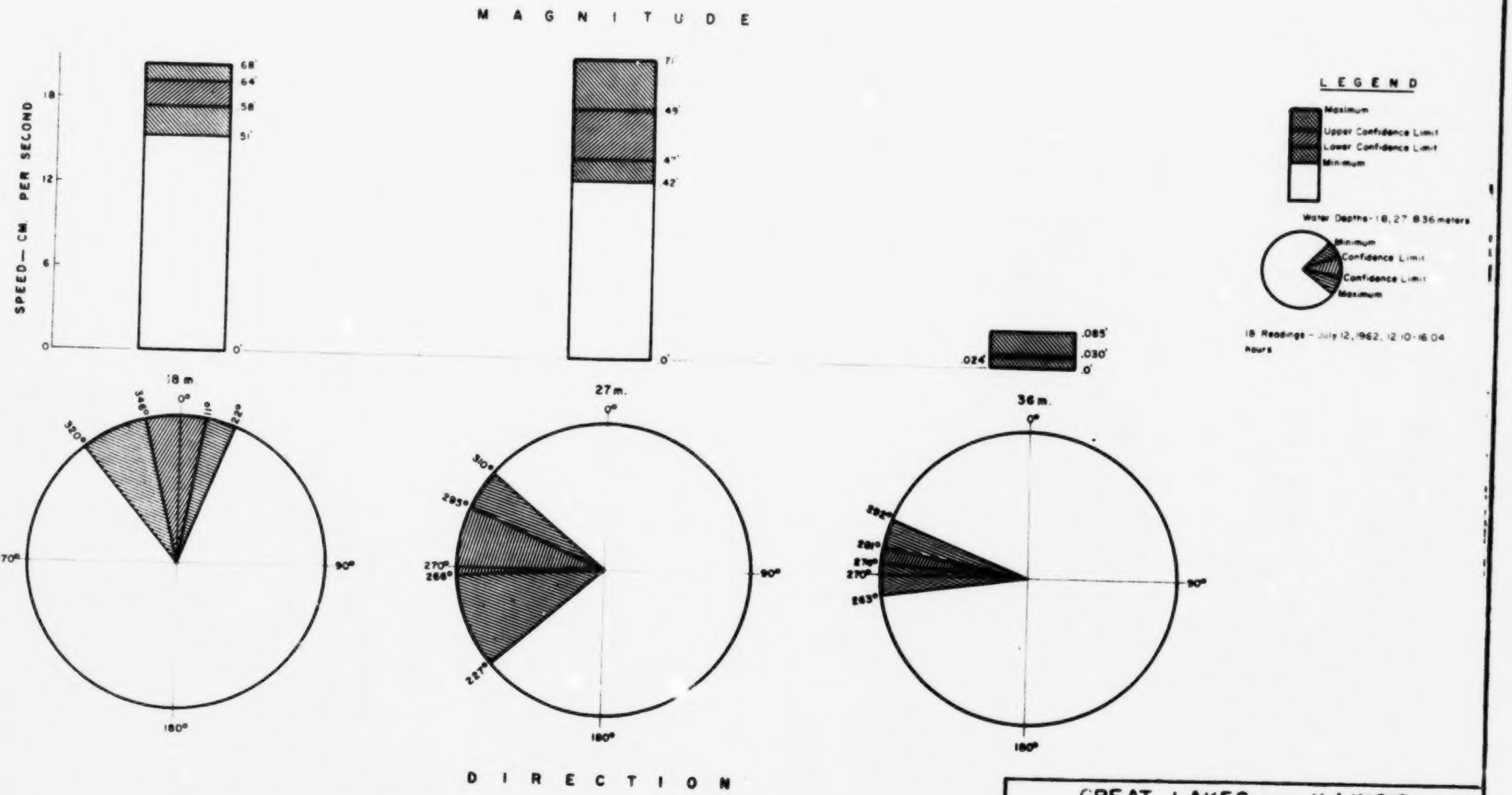
Mooring Characteristics

The original mooring system used by Dr. Richardson of Woods Hole in the Atlantic Ocean was modified for use in Lake Michigan. The Atlantic installation used a synthetic line anchored to the bottom and held at the surface by a large float. Ice and severe winter conditions prevented the use of a slack wire mooring system in Lake Michigan. The Project used a taut wire system with a subsurface float which has a positive buoyancy of 250 kilograms. A surface float, for use in ice-free periods, was attached by a slack line to the subsurface float. An examination of the original test data showed unusual variations in the direction vane. Observation disclosed that during windy periods the large surface float was capable of jerking the lower taut line in any direction. To prevent this action and the consequent swinging of direction vanes on the meters, the mooring system was changed to a two-line system. This present system leaves the meter line almost completely free from external stress.

Operational Characteristics

The mooring system used at the telemetry station had a small surface float relative to the subsurface float. Therefore, the pull of the surface float did not affect the direction vane on the sensors. Thus, the data from the telemetry station were used in the analysis of direction reliability. The 10-minute time intervals were used for the analysis. Figure 3-2 shows confidence limits using 10-minute intervals (Dixon, 27, p. 294). The results in Figures 3-3 to 3-6 show acceptable precision in both magnitude and direction at each of the depths (18, 27 and 36 m).

The Savonius rotor has been tested to determine its degree of reliability, response in turbulent motion, and dependability over periods of time. The rotor, as used, is sensitive to about 0.9 cm/sec as shown by tow tank tests conducted by the Corps of Engineers. Test by Gaul (34) indicates that the rotor is very reliable between 0.8 and 212 cm/sec.

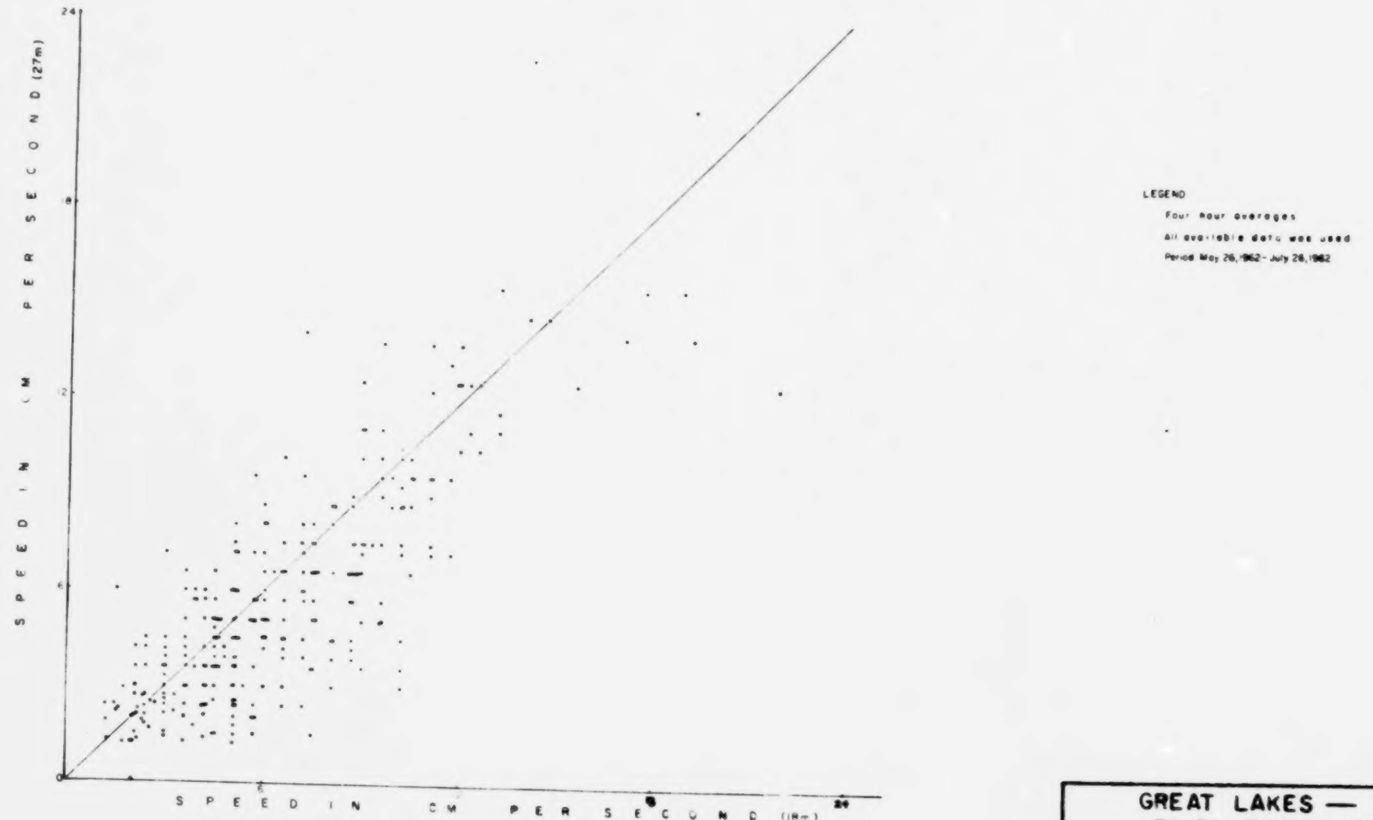


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

95% CONFIDENCE LIMITS FOR
MEDIAN SPEEDS & DIRECTIONS

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 3-2

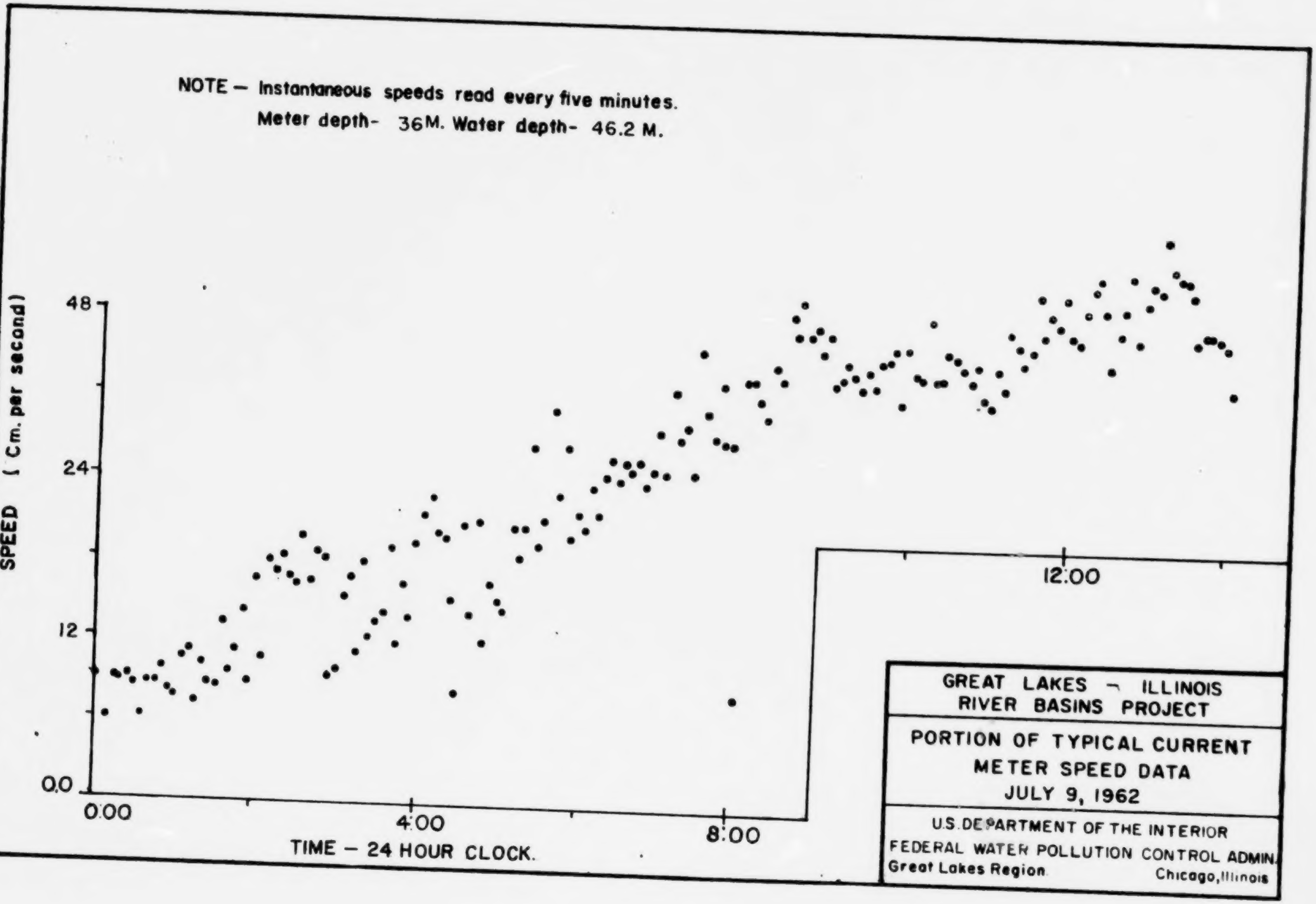


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

COMPARISON OF SPEEDS AT
18 METERS & 27 METERS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 3-3



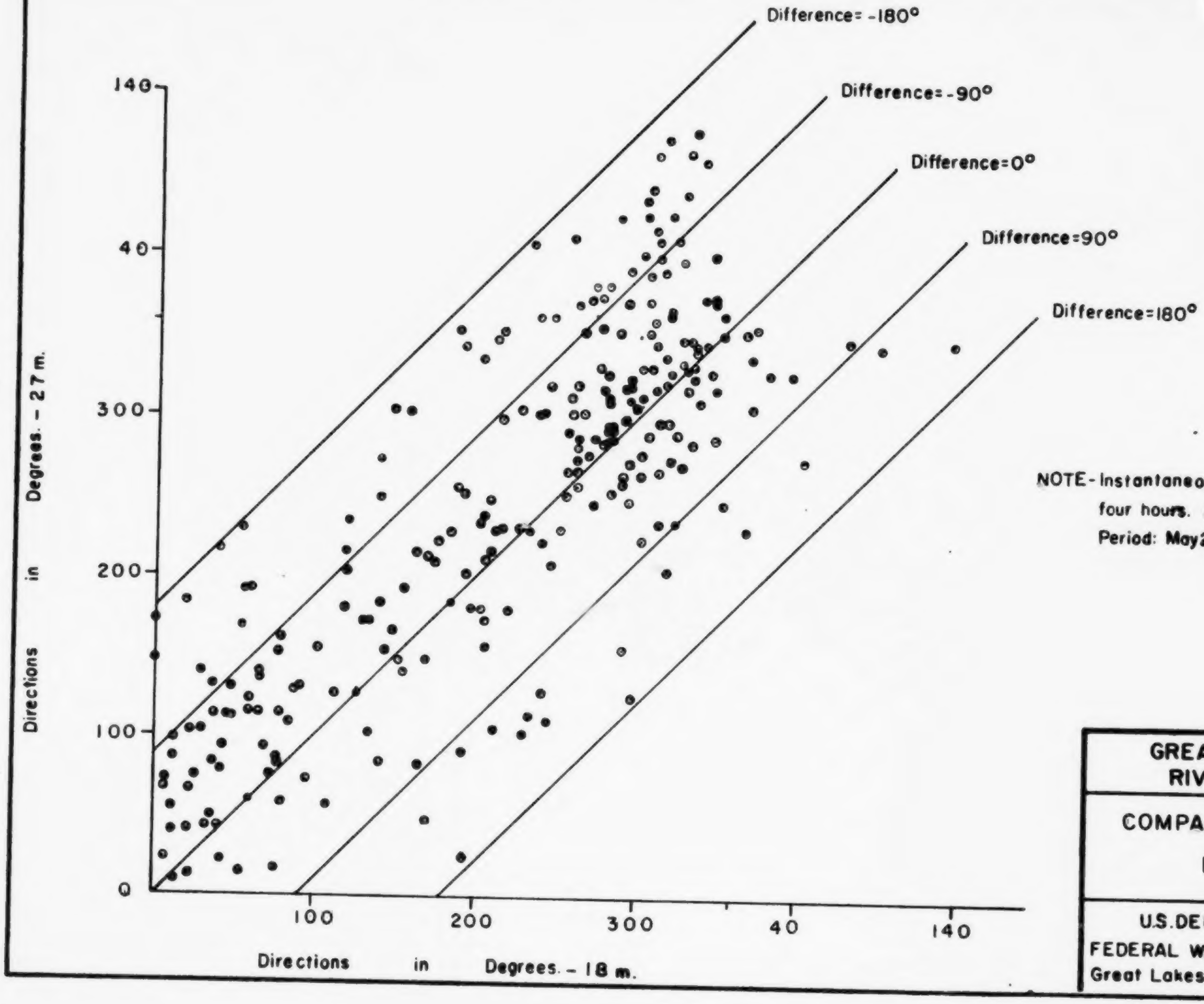
NOTE — Instantaneous speeds read every five minutes.
Meter depth- 36M. Water depth- 46.2 M.

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

PORTION OF TYPICAL CURRENT
METER SPEED DATA
JULY 9, 1962

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 3-4



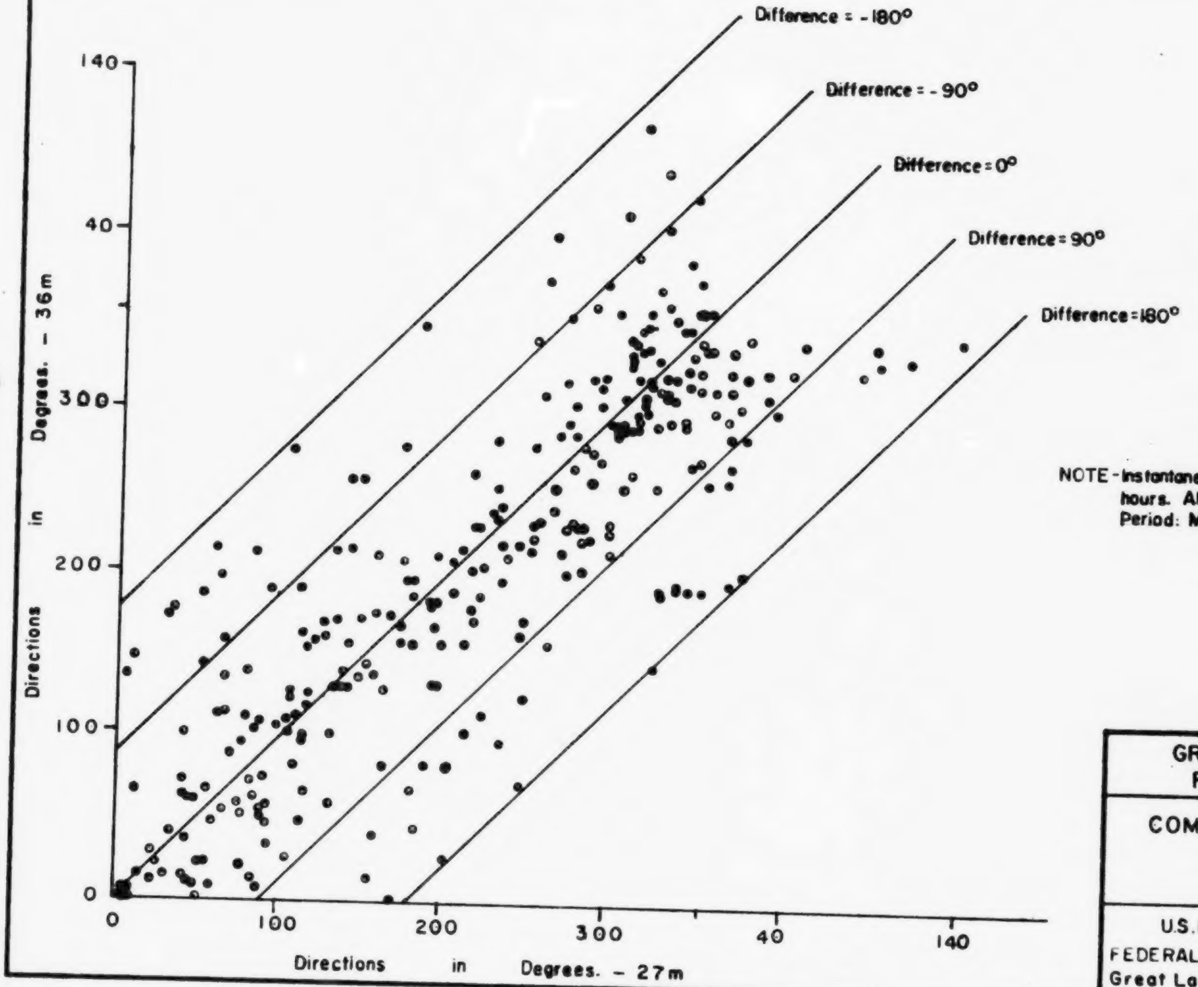
NOTE- Instantaneous directions read once every four hours. All available data were used.
Period: May 26, 1962 - July 26, 1962.

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

COMPARISON OF DIRECTIONS
18M. & 27M.

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 3-5



NOTE - Instantaneous directions read once every four hours. All available data were used.
Period: May 26, 1962 - July 26, 1962.

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

COMPARISON OF DIRECTIONS
27 M. & 36 M.

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 3-6

The rotor is omnidirectional, which means that it will sense motion from any direction in a horizontal plane when set with its axis of rotation vertical. The orbital motion of waves produces a surge forward and then backward as it passes. This effect on a Savonius rotor would show as an increased speed. Wave action, during severe weather conditions, can be detected as deep as 15 m. For this reason, the uppermost current meter is at the 10-m level and will only be affected during the more adverse conditions. Figure 3-8 shows a typical rating curve for the rotor made by the Corps of Engineers.

Flow Characteristics

A preliminary examination was made of the flow data. The following were investigated: relationship between wind and water movement, relationship between readings at different stations, relationship between readings at different levels, range of speeds, and possible predominant directions at different speeds.

Much of the report depends on statistical testing for relationships or correlations between two variables. A positive result (correlation) implies 95-percent confidence that a relationship or correlation does exist. A negative result (no correlation) implies one of the following two possibilities: either no relationship exists between the variables in question or a relationship does exist but the nature of the statistical test or the data was such that the relationship could not be detected.

Two limitations on the applicability of the findings in this report should be mentioned. The current meter data represent samples from a changing physical system. Thus, physical relationships which may occur for one period of time may not necessarily occur for any other period of time. For example, it is possible that systematic seasonal differences are not reflected in the tests reported herein. Also, the relations which are here established represent average effects. The only thing necessary to produce a nonrandom effect during the whole period of time is a large enough nonrandom effect to balance out this effect on the overall result. The conclusion that can be obtained from a positive result is that one can expect (with 95 percent confidence) that the result held more than 50 percent of the time, for the period of study (Dixon, 27, p. 280).

Winds and Currents

An attempt was made to correlate wind and current data. Wind data were estimated (from shore based stations) for the 10-m level (above the lake surface) and the current data were taken at 20 m below the surface. Various relationships were tried, using a variety of ways of weighing past wind averages and correlating with present currents. No positive correlation could be found. This does not necessarily mean that wind does not affect water currents. There is every reason to assume that such relationship exists, but detection is difficult at the greater depths.

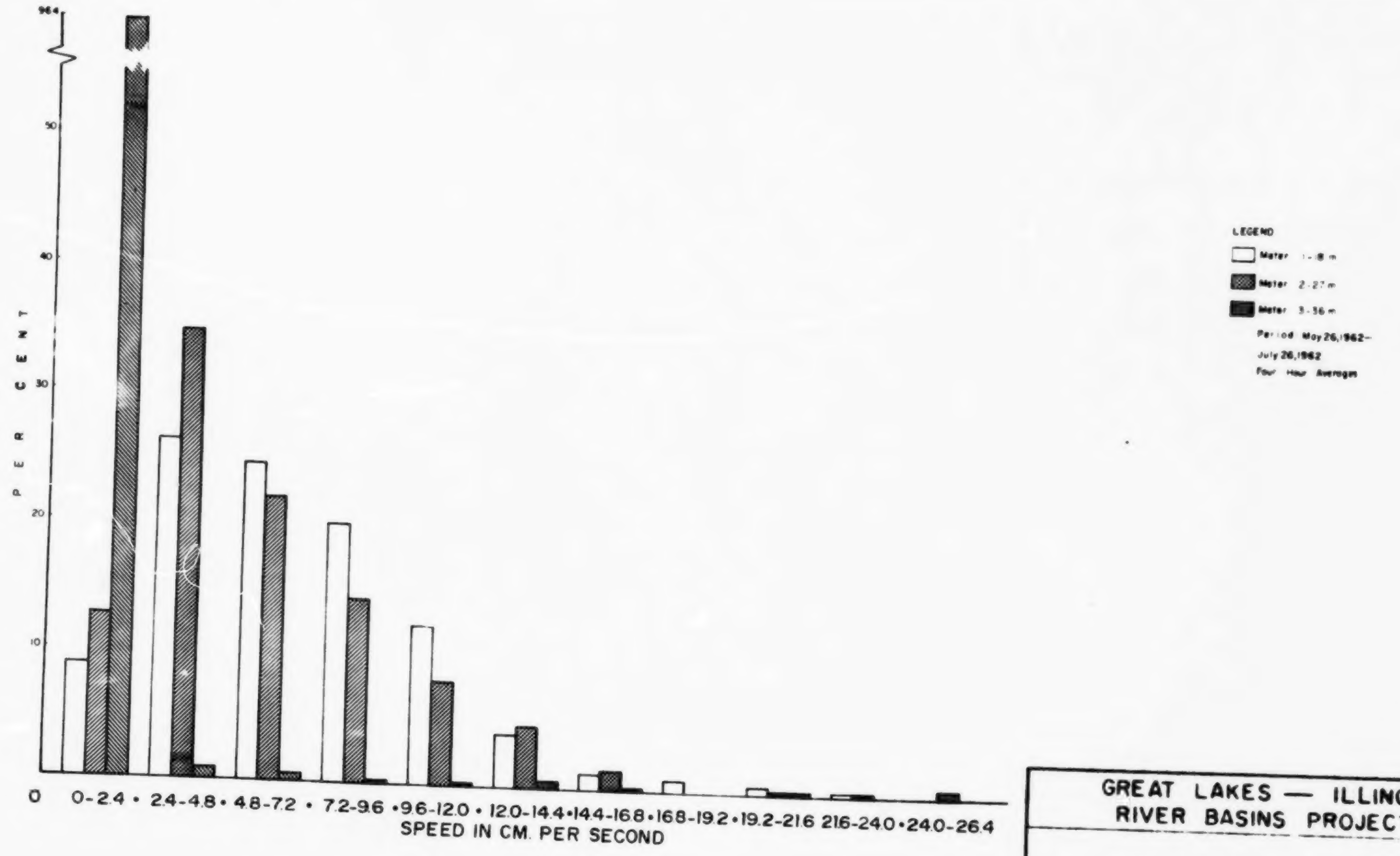
Correlation Between Meters at one Station

A test was made to correlate currents at different depths (18, 27, and 36 m) at the same station. Both magnitude and direction showed positive correlation at 95 percent confidence. Figure 3-3 shows the magnitude (speed) relationship at 18 and 27 m. The positive correlation can easily be seen. It can also be seen that the speeds at 18 m are greater than speeds at 27 m on the average (a difference in medians at 95 percent confidence is shown). Speeds at the 36-m depth were generally lower than the minimum detectable speeds on the current meter. Figures 3-5 and 3-6 compare directions at different depths. The mean direction of current, for the whole period at 30 m, was to the right of that at 20 m, whereas the mean at 40 m appeared slightly to the left of that at 30 m, with 95 percent confidence. While the first result might be considered as consistent with Ekman transport (75), the second result is zero. As far as they go, these results confirm that, because of shallow depth and seasonal stratification, fully developed Ekman spiral flow will rarely be encountered in Lake Michigan.

Figure 3-7 is a histogram which is designed to show the range of speeds at different depths. The abscissa is a group of speed ranges and the ordinate is the percent of time that the readings fall into the range specified in the abscissa. There are differences in speeds at different depths, and the greater speeds are the bars which are farther to the right.

Figures 3-9 and 3-10, show polar coordinate diagrams of speed and direction at two of the depths observed. Table 3-1 shows the number and percent of observations in each quadrant, the average angle and speed for each quadrant, and the maximum number of times the current was found in a specific quadrant. The number of times the readings were in the northwest quadrant was unusually high, indicating a 95 percent probability nonrandom effect (Tate, 76, p. 35). One meter showed northwest currents over four days in succession, Table 3-1.

The results of these preliminary tests in one area of the Lake may be summarized as follows. The two current meters in the same area showed, on the average, correlation in direction and general correlation in speed and direction at different depths. In general, speed decreased with depth, and average shifts in direction at different

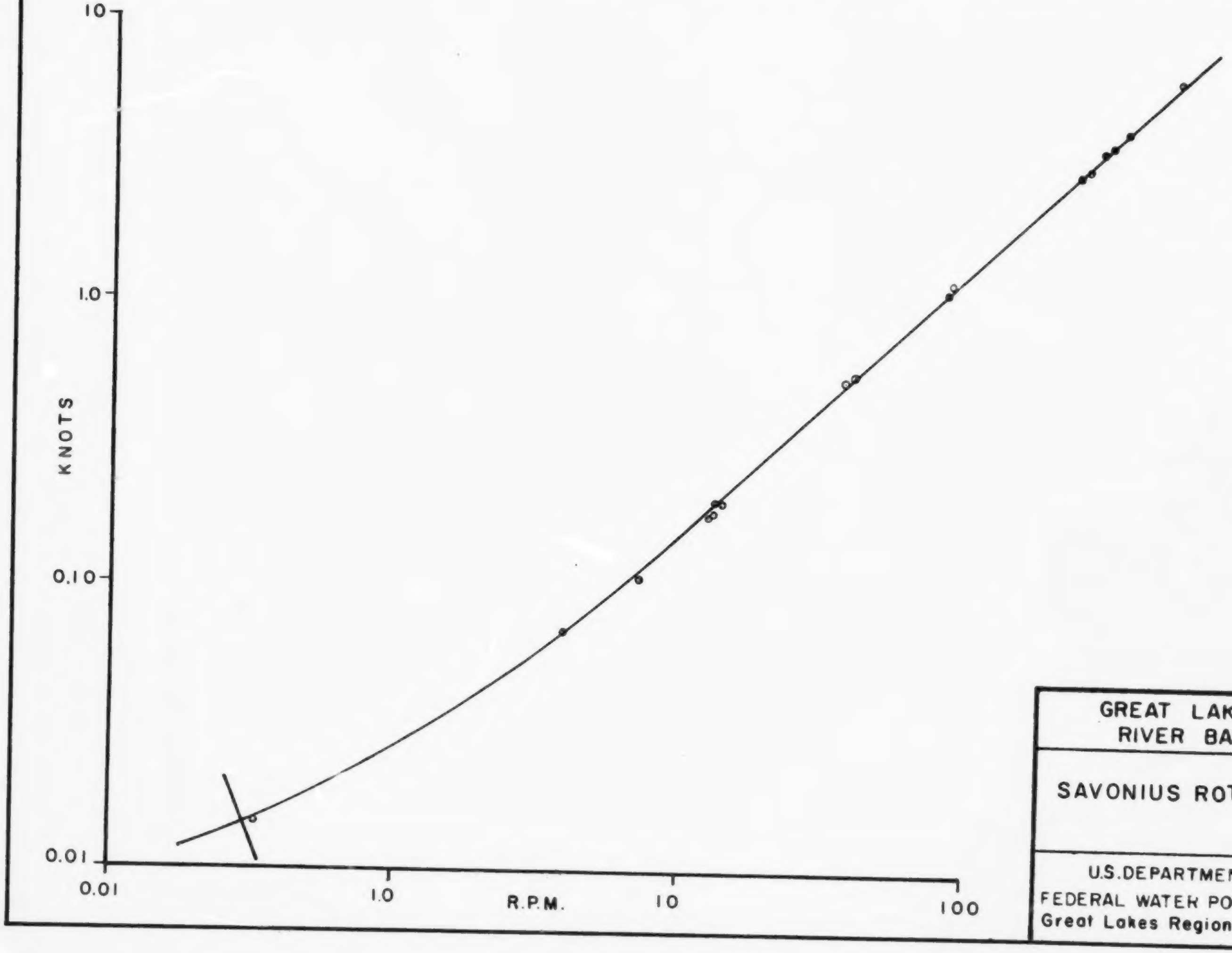


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

HISTOGRAM OF SPEED
AT THREE LEVELS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 3–7

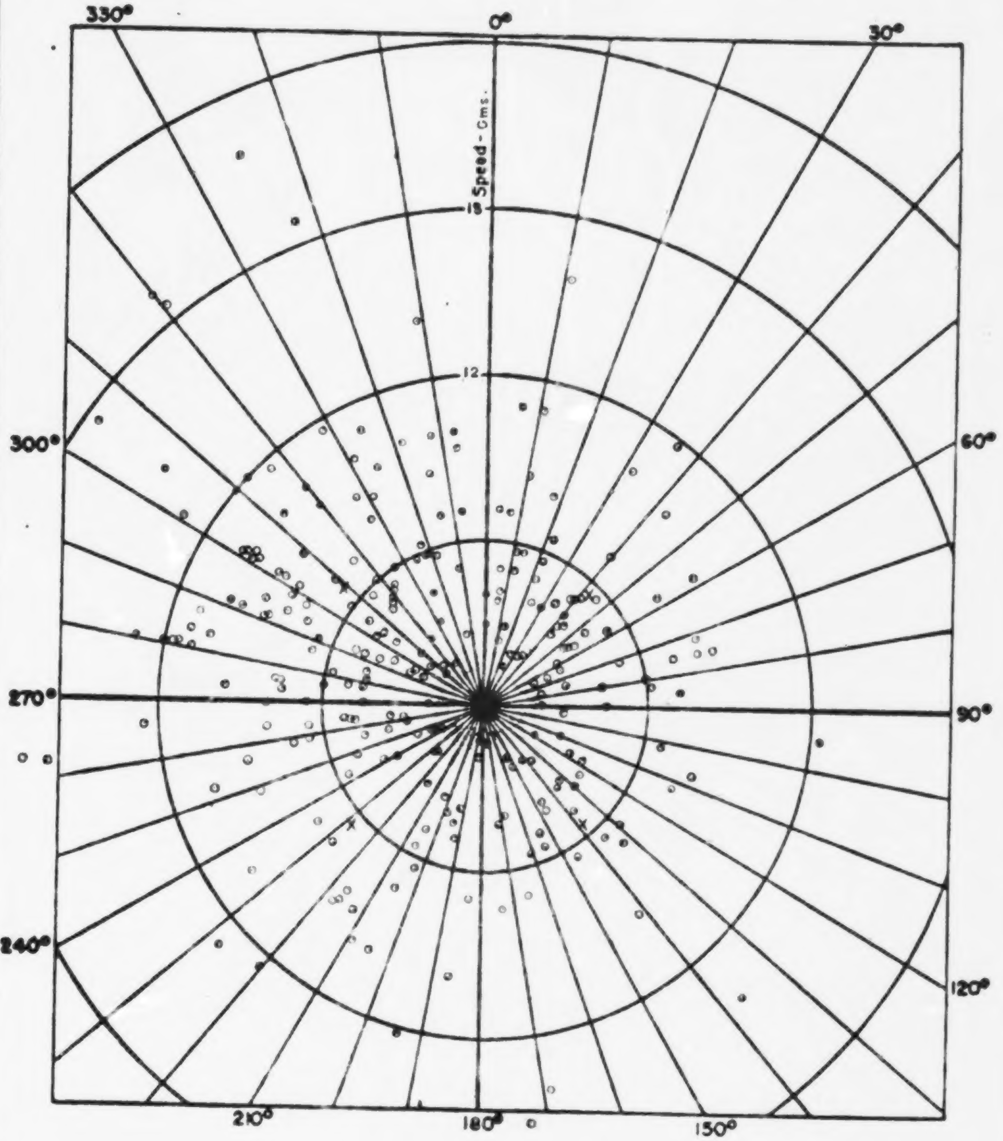


GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

SAVONIUS ROTOR CALIBRATION

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 3-8



NOTE:

Speed averaged over four hours. Instantaneous direction measured at end of each period.

Period: May 26, 1962 – July 26, 1962

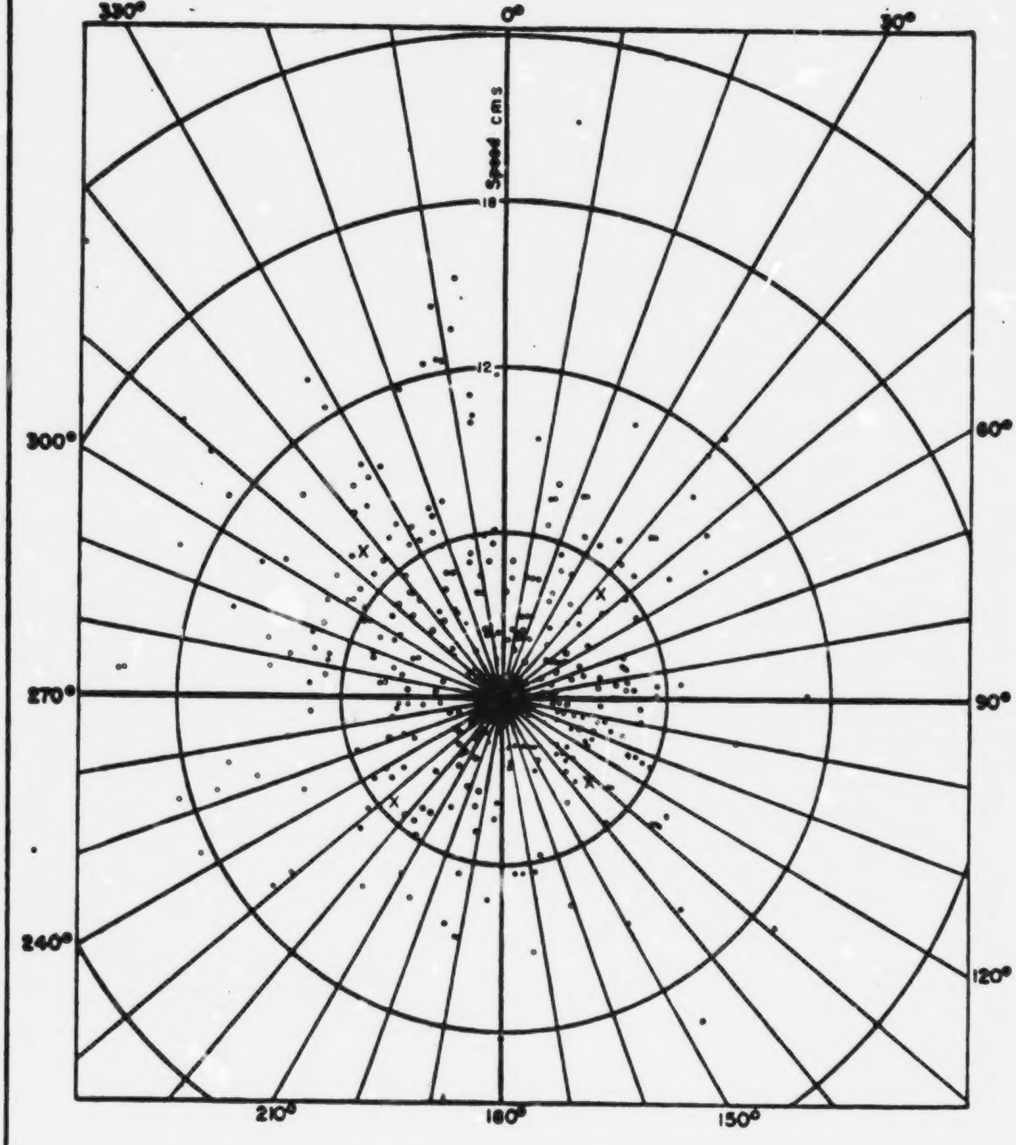
X Average velocity for quadrant

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

POLAR DIAGRAM OF MAGNITUDE
AND DIRECTION AT 18 M.

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 3-9



NOTE:

Speed averaged over four hours. Instantaneous direction measured at end of each period.

Period: May 26, 1962 - July 26, 1962.
The three points located outside the graph limits are: 310°, 24 Cms. 286°, 23 Cms. and 252°, 19 Cms.
X Average velocity for quadrant

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

POLAR DIAGRAM OF MAGNITUDE AND
DIRECTION AT 27 M.

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 3-10

TABLE 3-1

Current Meter Readings in Each Quadrant*

Quadrant	Maximum Consecutive Readings in Quadrant	Observation		Average**	
		Number	Percent of Time	Magnitude CM/SEC	Direction Degrees
Meter 1 - 18 M Deep					
0-90°	4	62	24.3	5.6	42
90-180°	3	33	12.9	5.8	139
180-270°	3	58	22.8	6.6	228
270-360°	20	102	40.0	6.8	310
			100.0		
Meter 2 - 27 M Deep					
0-90°	4	77	25.6	5.3	43
90-180°	9	59	19.7	4.4	131
180-270°	5	60	20.0	5.6	228
270-360°	26	104	34.7	7.7	316
			100.0		
Meter 3 - 36 M Deep					
0-90°	3	66	22.0	0.54	38
90-180°	6	63	21.0	0.012	138
180-270°	3	73	24.3	0.015	223
270-360°	13	98	32.7	0.33	314
			100.0		

*Readings are approximately four hours apart.
**Arithmetic average of magnitude and direction.

depths were detected. For instance, the mean current direction at 27 m lay to the right of that at 18 m. The currents at 36 m appeared to the left of those at 27 m. As mentioned earlier, the current speeds at 40 m were frequently below the minimum threshold capability of the rotor. It is probable that the vane response to movement was also close to its minimum range of detection. The speed ranges are shown on the histogram plotted. The polar coordinate diagrams and Table 3-1 indicate a predominance of currents from the northwest during the period sampled.

Significance of Findings

The data show that an effluent discharged into the Lake, at any depth, can have a prevailing direction of movement. During the period of May to July 1962, this movement at the test station would normally have been from the northwest at the three levels observed. The maximum consecutive readings from the northwest varied from three to more than four days with an average drift of seven or more kilometers per day for the 18- and 27-meter levels. The rate of flow is expected to be higher in the upper layers.

Although mixing occurs during severe weather conditions the exact rate or amount are unknown. Earlier studies when the Chicago River was diverted into the Lake in September 1961, show that the discharged waters maintained a detectable coliform count for 5 days, (82). Therefore, it may be possible that even during periods of high velocities for 8 or more hours the effluent will not be mixed into the surrounding water.

The worst condition appears to be when an effluent remains in the general vicinity of its discharge point because of extremely low velocities. After a period of building-up, the concentrated effluent might then be moved, en masse, by the current. Relatively slow currents could move the effluent for 4 or more days in one direction, as shown in Table 3-1, or a fast moving current could produce the same result within 5 to 8 hours.

This is the first occasion on which current meters have been operated for continuous periods in Lake Michigan and, although they demonstrate average trends, they also show a far greater variability of flow than that indicated by previous studies.

Summary of Test Studies

The data and performance tests from the first meters set in Lake Michigan were examined and evaluated. The tests were made to evaluate the type of meters to be used and reliability of the instruments' internal components. The test data were examined for persistency of movement and the variations of speed with depth.

The data tabulated for May to July 1962, show that under certain conditions an effluent could move, at low speed with relatively little mixing, for over 4 days. Movement during other periods of the year may show that there are other quadrants in which the current will predominate for longer periods of time.

The test data indicated that the reliability and sensitivity of all meters for measuring both speed and direction were satisfactory for study purposes. The data from the instruments using one type of mooring system indicated that the large surface float had an effect on the vane direction. An alternate mooring system was devised to eliminate this possible source of error.

Three types of meter systems were evaluated and the Woods Hole meter was selected because of the established performance record of its internal components, type of data collected, and lower cost.

CHAPTER 4

METHODS FOR MOORINGS, INSTRUMENT CHECKS, FILM PROCESSING AND FILM CONVERSION

Introduction

To successfully complete the largest current study ever planned, new methods and techniques had to be devised to insure reliability, efficiency, and standardization.

The instrumentation used was designed and tested at the Woods Hole Oceanographic Institution. Since these instruments were relatively new, they have undergone some modification with time.

An instrument shop was established at each field station where operations were being conducted. An instrument technician and assistant were in charge of all repairs, loading and unloading film, and calibration systems.

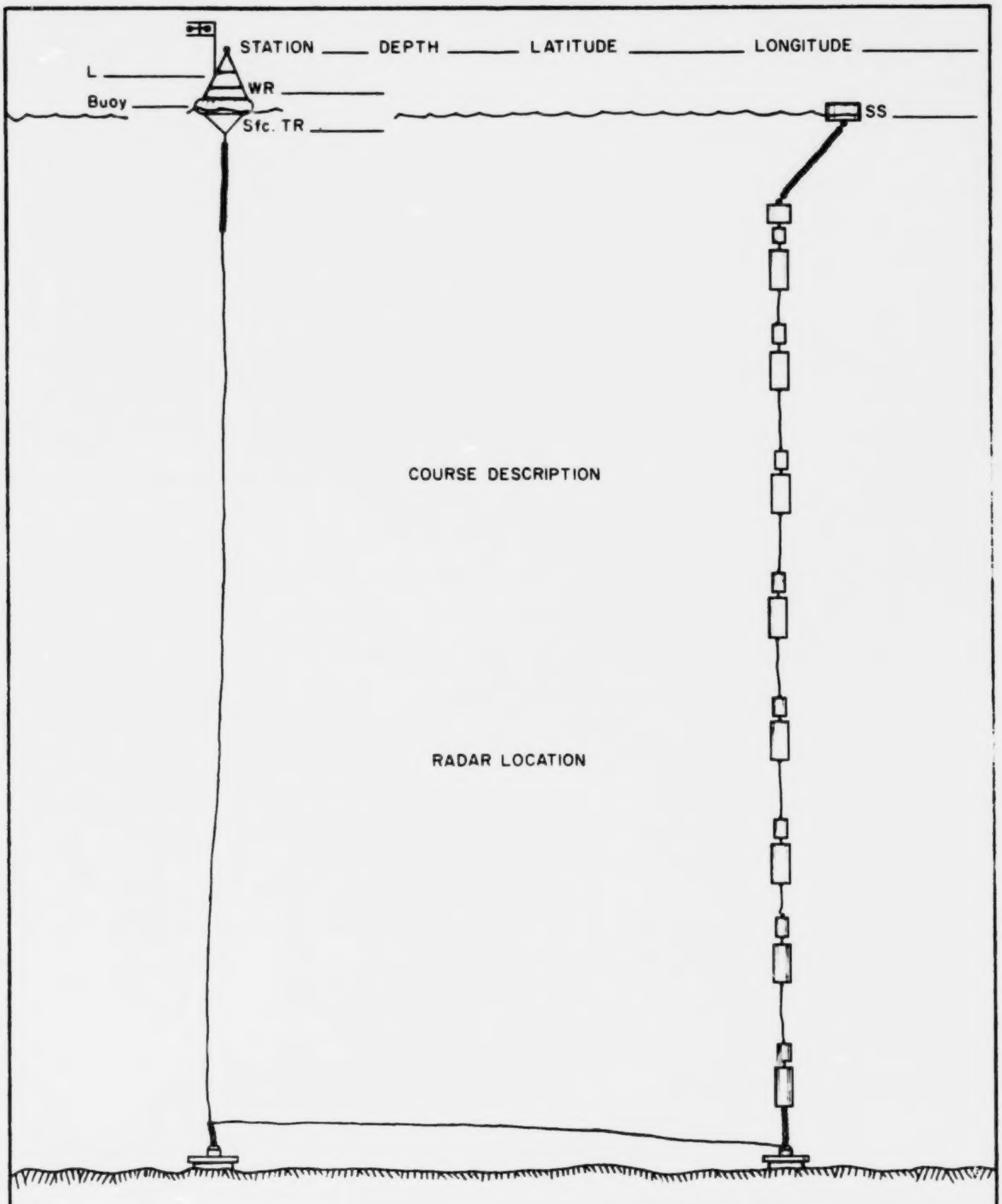
Prior to each station installation, the instruments are given a complete mechanical check. This checking includes the following instruments: current meters, temperature recorders, anemometers, lights, and recovery buoys.

In setting a station, a form is filled out showing all instrument serial numbers, line lengths, etc. A sample diagram is shown in Figure 4-1.

Mooring Systems

The meter mooring system used by the Federal Water Pollution Control Administration in the Great Lakes has been basically standardized with minor modifications as the program progressed.

The system used during the ice-free season is shown in Figure 4-2. The current meters, each paired with a water temperature recorder, were suspended in a taut line between a subsurface buoy and anchor. A slack line connected this anchor to another nearby anchor which moored, on a slack line, a surface buoy. The surface buoy was instrumented with a water temperature recorder, a wind recorder, and a navigation light. Ordinarily, a small surface float was attached to the subsurface buoy by a 0.6-cm ($\frac{1}{4}$") slack manila line, and a staff marker buoy was set separately but nearby. These markers were set to help assure station recovery.

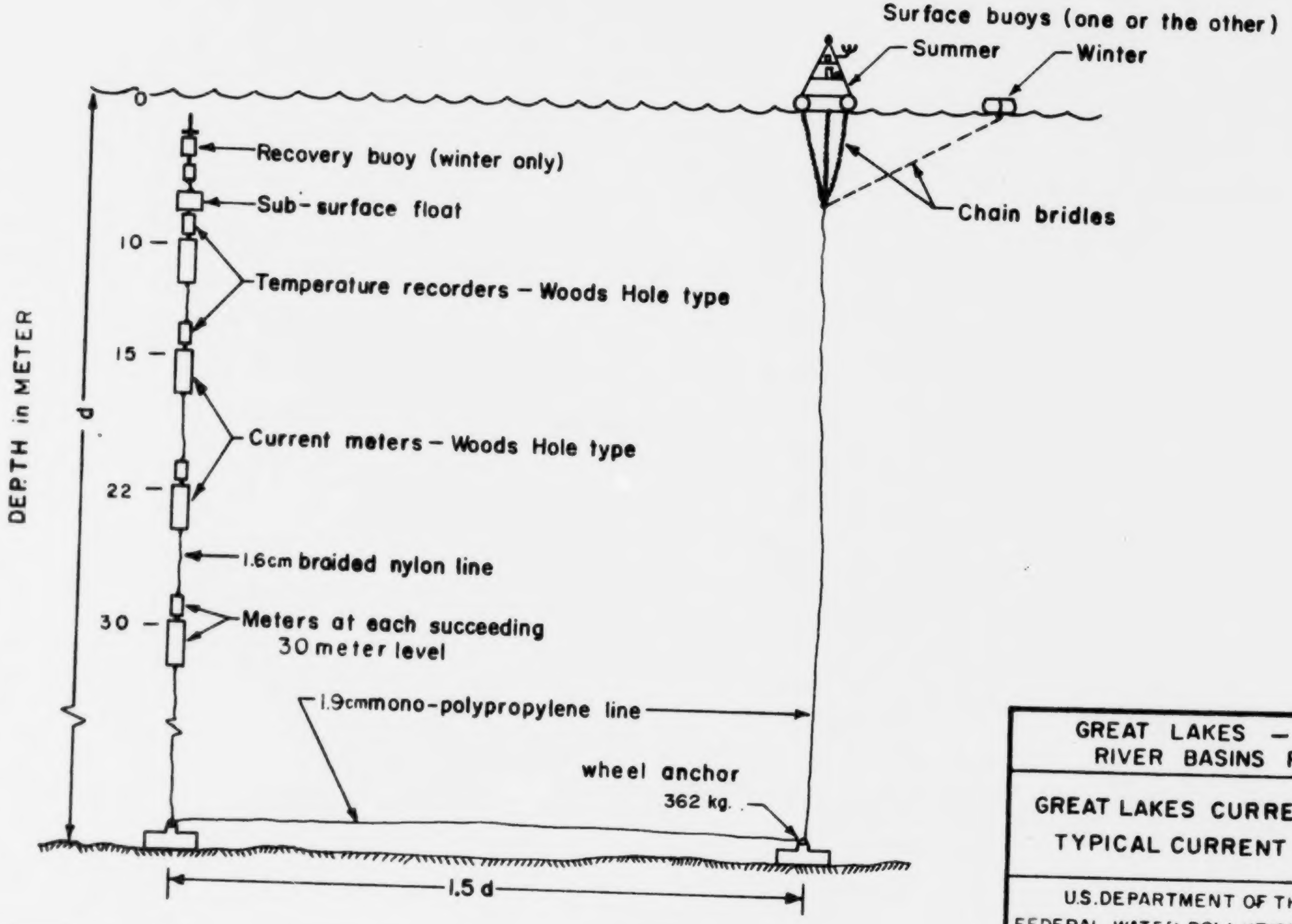

STATION
DEPTH
LATITUDE
LONGITUDE
L
WR
Buoy
Sfc. TR
SS
COURSE DESCRIPTION
RADAR LOCATION

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STATION DIAGRAM
SUMMER

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-1


Surface buoys (one or the other)
Summer
Winter
Chain bridles
0
Recovery buoy (winter only)
Sub-surface float
10
Temperature recorders – Woods Hole type
15
Current meters – Woods Hole type
22
1.6cm braided nylon line
30
Meters at each succeeding 30 meter level
1.9cm mono-polypropylene line
wheel anchor 362 kg.
DEPTH in METER
d
1.5 d

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

GREAT LAKES CURRENT STUDY
TYPICAL CURRENT STATION

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-2

Winter metering stations were similar except the instrumented surface buoy was replaced by a subsurface recovery buoy set to surface in the spring by use of a clock-controlled actuator (Figures 4-3 and 4-4). A second recovery buoy was attached to the main subsurface buoy to help assure recovery, Figure 4-5.

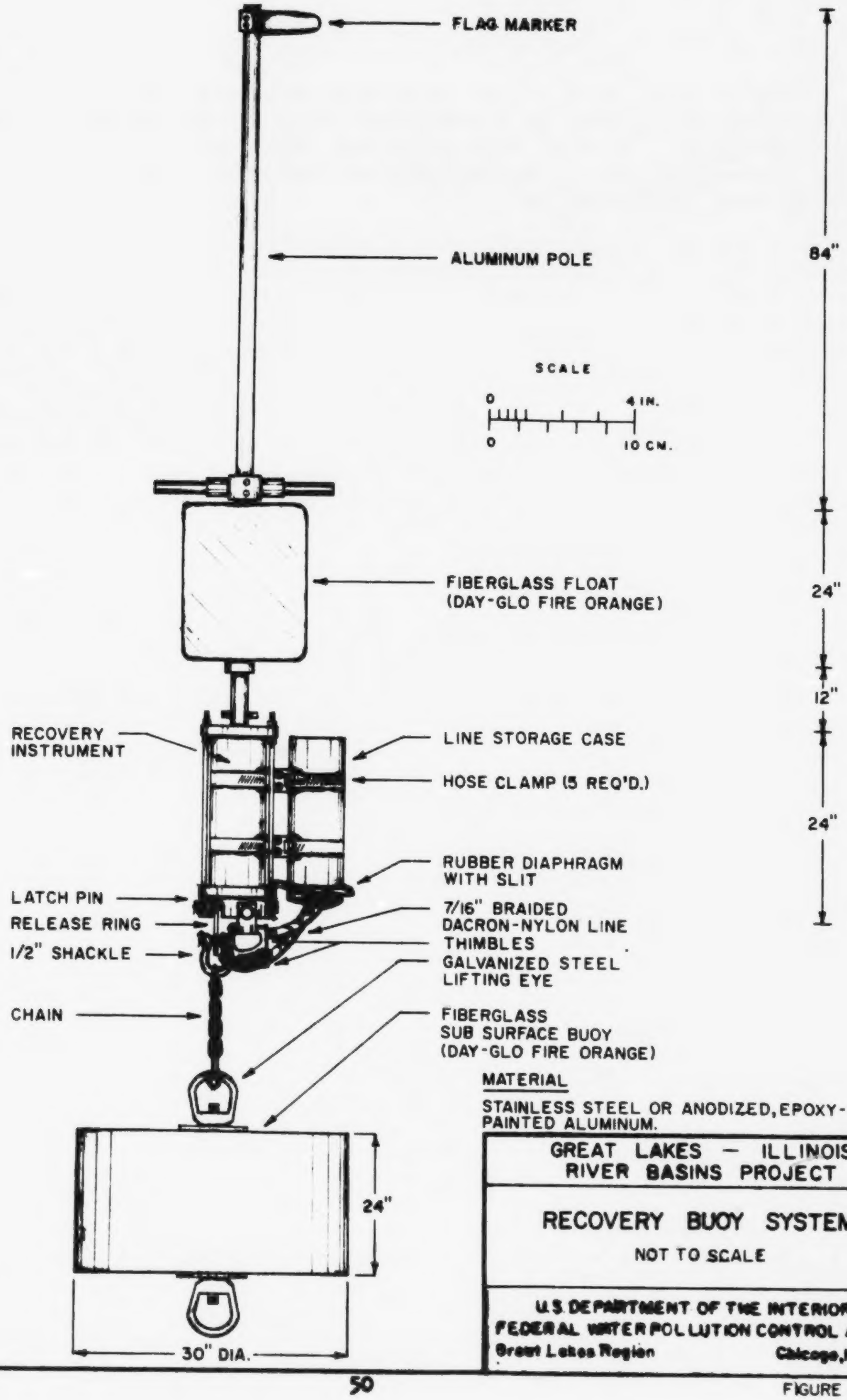
In detail, a metering station consisted of the following array beginning with the subsurface support buoy (Figure 4-6). The top of the subsurface buoy was approximately 7.2 m below the water surface. A temperature recorder (Figure 4-7) was attached to the bottom of the subsurface buoy with a 1.2-cm shackle. The temperature recorder was attached to a current meter (Figure 4-8). At the bottom of the current meter was shackled a 1.2-cm (½") by 12.5-cm (5") ring. The ring, in turn, was shackled to a thimbled, 1.6-cm (5/8") braided polypropylene line, 3.3 m long. At the bottom of the 1.9-cm (3/4") line another temperature recorder was shackled and the sequence repeated. In this manner, current meter-temperature recorder pairs were set at approximate depths of 10, 15, 22, and 30 m and every 30 m thereafter, depending upon total water depth.

The bottom of the instrument line was attached by a length of 1.0-cm (3/8") chain and shackles to a 362-kg railroad car wheel anchor (Figure 4-9).

Another short length of chain was shackled to the instrument anchor. Polypropylene 1.9-cm (3/4") rope was shackled to the chain and leads across the bottom to a second wheel anchor at a distance equal to or exceeding 1½ times the water depth. The rope was again attached to the second anchor by a short length of chain. At the juncture of the rope and chain was a 1.6-cm (5/8") by 12.6-cm (5") steel ring (Figure 4-10). To this ring the instrumented surface buoy was moored by 1.9-cm (3/4") polypropylene rope. This rope was slack and leads up to a 6-m length of 1.0-cm (3/8") chain, which in turn was shackled to the buoy bridle. After some difficulty was experienced in pulling this anchor, a weak link of 1.2-cm (½") polypropylene rope was put into the system between the anchor chain and ring.

A temperature recorder was installed in the bridle of the surface buoy (Figure 4-11). A navigation light (Figure 4-12) was mounted on the top platform of the buoy tower. A wind recorder (Figure 4-13) was mounted on the lower platform. Its velocity sensor was mounted atop a pipe about 61 cm (2') above the top of the buoy tower, 3.6 m above the water surface (Figure 4-14). The surface and other buoys are shown in Figures 4-15 and 4-16.

The entire station array is assembled on deck prior to launching. The subsurface buoy and attached instrument group are put in the


FLAG MARKER
ALUMINUM POLE
84"
SCALE
0
4 IN.
0
10 CM.
FIBERGLASS FLOAT
(DAY-GLO FIRE ORANGE)
24"
12"
RECOVERY INSTRUMENT
LINE STORAGE CASE
HOSE CLAMP (5 REQ'D.)
24"
RUBBER DIAPHRAGM WITH SLIT
LATCH PIN
RELEASE RING
1/2" SHACKLE
7/16" BRAIDED DACRON-NYLON LINE
THIMBLES
GALVANIZED STEEL LIFTING EYE
CHAIN
FIBERGLASS SUB SURFACE BUOY
(DAY-GLO FIRE ORANGE)
24"
30" DIA.

MATERIAL

STAINLESS STEEL OR ANODIZED, EPOXY-PAINTED ALUMINUM.

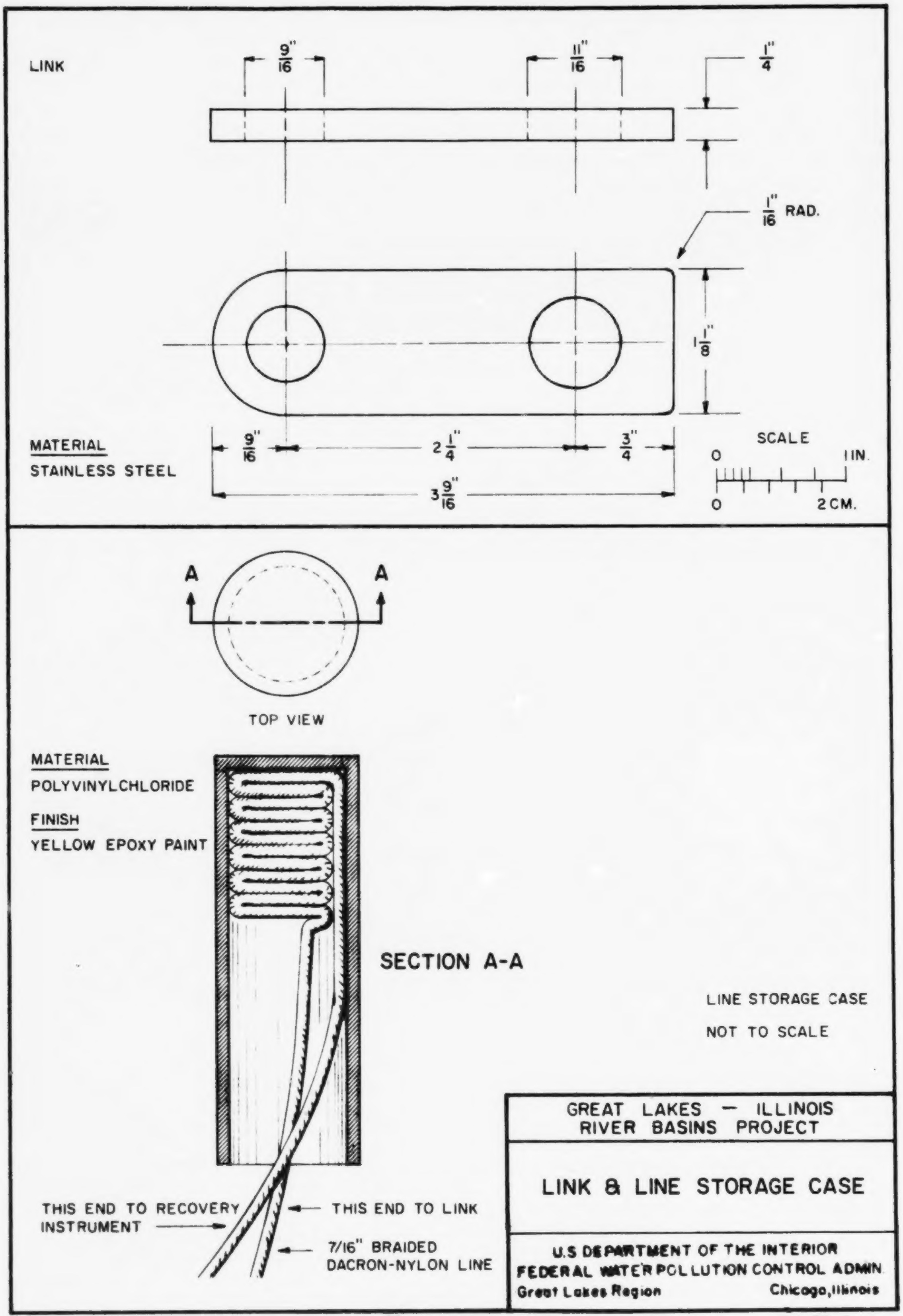
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

RECOVERY BUOY SYSTEM

NOT TO SCALE

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-3

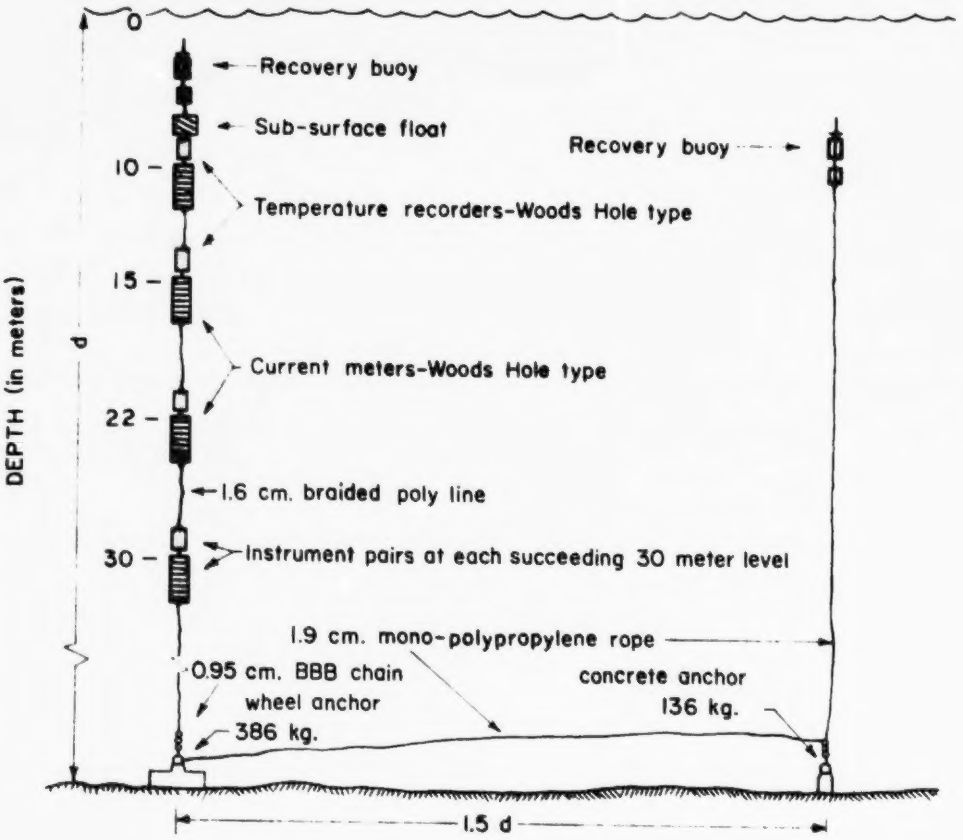

LINK
9" 16
11" 16
1" 4
1" 16 RAD.
1 1" 8
MATERIAL
STAINLESS STEEL
9" 16
2 1" 4
3" 4
3 9" 16
SCALE
0
1 IN.
0
2 CM.
A
A
TOP VIEW
MATERIAL
POLYVINYLCHLORIDE
FINISH
YELLOW EPOXY PAINT
SECTION A-A
LINE STORAGE CASE
NOT TO SCALE
THIS END TO RECOVERY INSTRUMENT
THIS END TO LINK
7/16" BRAIDED DACRON-NYLON LINE

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LINK & LINE STORAGE CASE

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-4


0
Recovery buoy
Sub-surface float
Recovery buoy
10 –
Temperature recorders-Woods Hole type
15 –
DEPTH (in meters)
d
Current meters-Woods Hole type
22 –
1.6 cm. braided poly line
30 –
Instrument pairs at each succeeding 30 meter level
1.9 cm. mono-polypropylene rope
0.95 cm. BBB chain
wheel anchor
386 kg.
concrete anchor
136 kg.
1.5 d

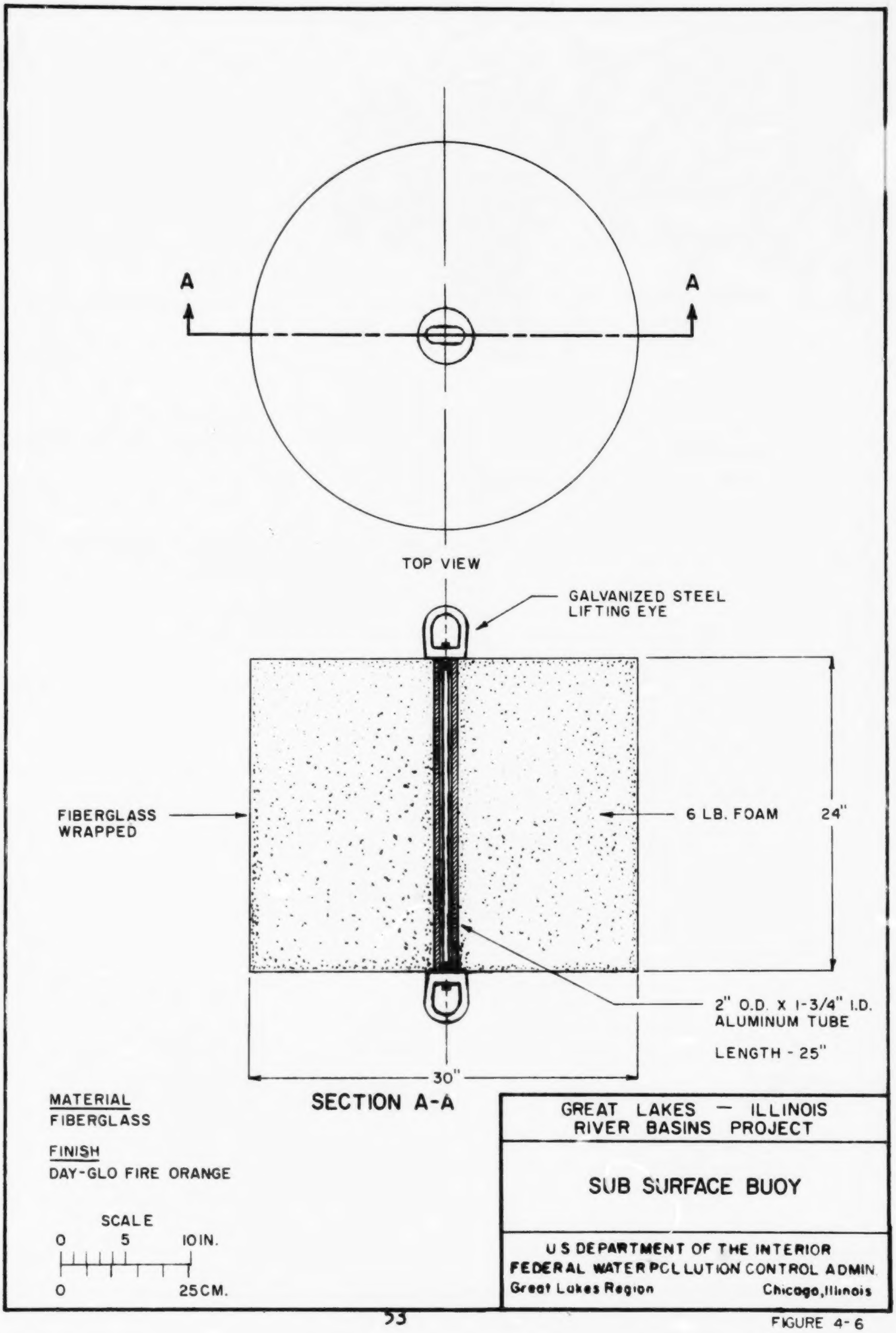
NOT TO SCALE

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

TYPICAL CURRENT STATION
WINTER

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-5

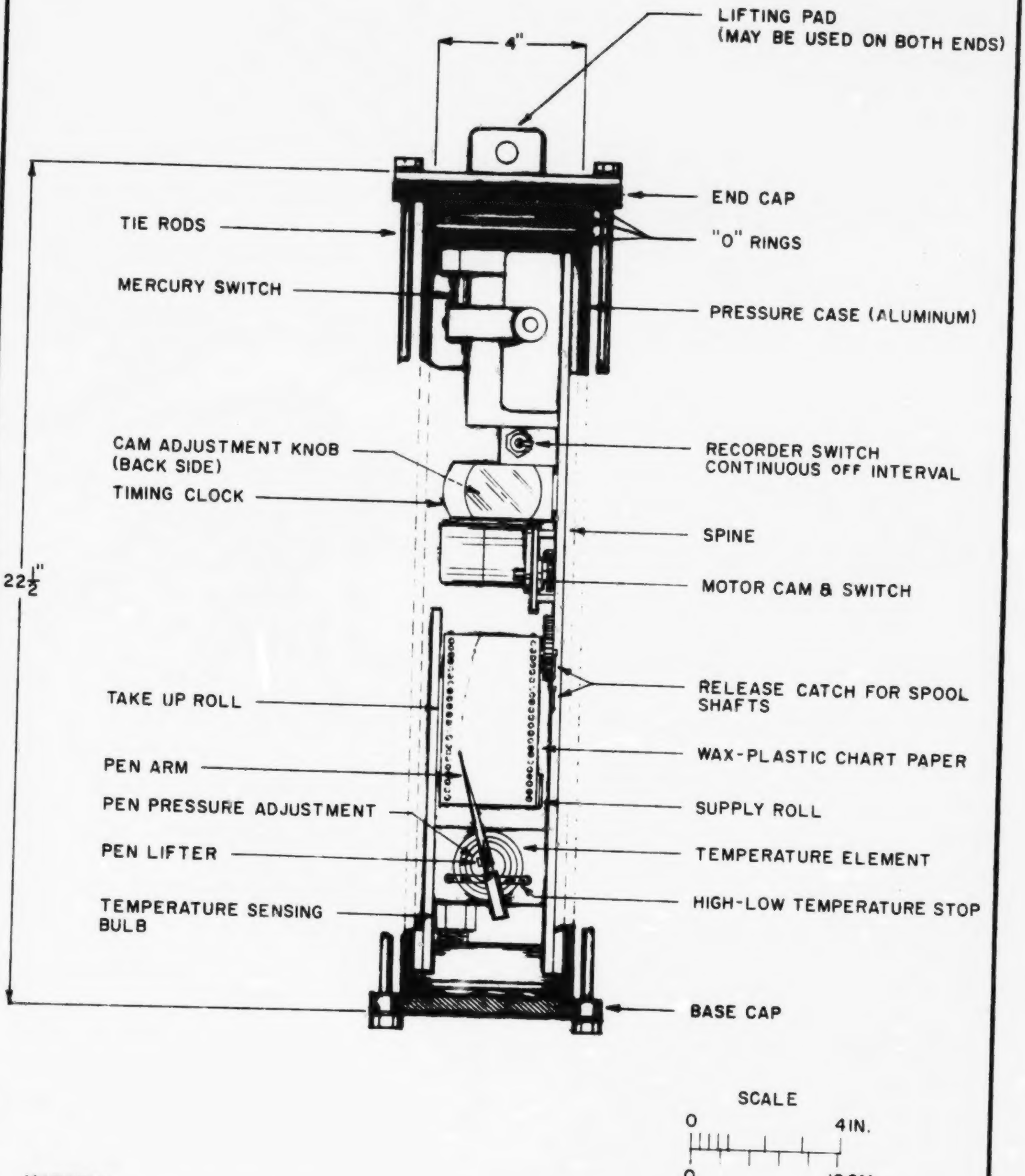

A
A
TOP VIEW
GALVANIZED STEEL LIFTING EYE
FIBERGLASS WRAPPED
6 LB. FOAM
24"
2" O.D. X 1-3/4" I.D. ALUMINUM TUBE
LENGTH - 25"
30"
SECTION A-A
MATERIAL
FIBERGLASS
FINISH
DAY-GLO FIRE ORANGE
SCALE
0
5
10 IN.
0
25 CM.

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUB SURFACE BUOY

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-6


LIFTING PAD
(MAY BE USED ON BOTH ENDS)
4"
END CAP
TIE RODS
"O" RINGS
MERCURY SWITCH
PRESSURE CASE (ALUMINUM)
CAM ADJUSTMENT KNOB
(BACK SIDE)
RECORDER SWITCH
CONTINUOUS OFF INTERVAL
TIMING CLOCK
SPINE
22½"
MOTOR CAM & SWITCH
TAKE UP ROLL
RELEASE CATCH FOR SPOOL SHAFTS
PEN ARM
WAX-PLASTIC CHART PAPER
PEN PRESSURE ADJUSTMENT
SUPPLY ROLL
PEN LIFTER
TEMPERATURE ELEMENT
TEMPERATURE SENSING BULB
HIGH-LOW TEMPERATURE STOP
BASE CAP
SCALE
0
4 IN.
0
10 CM.

MATERIAL
ALUMINUM & STAINLESS STEEL

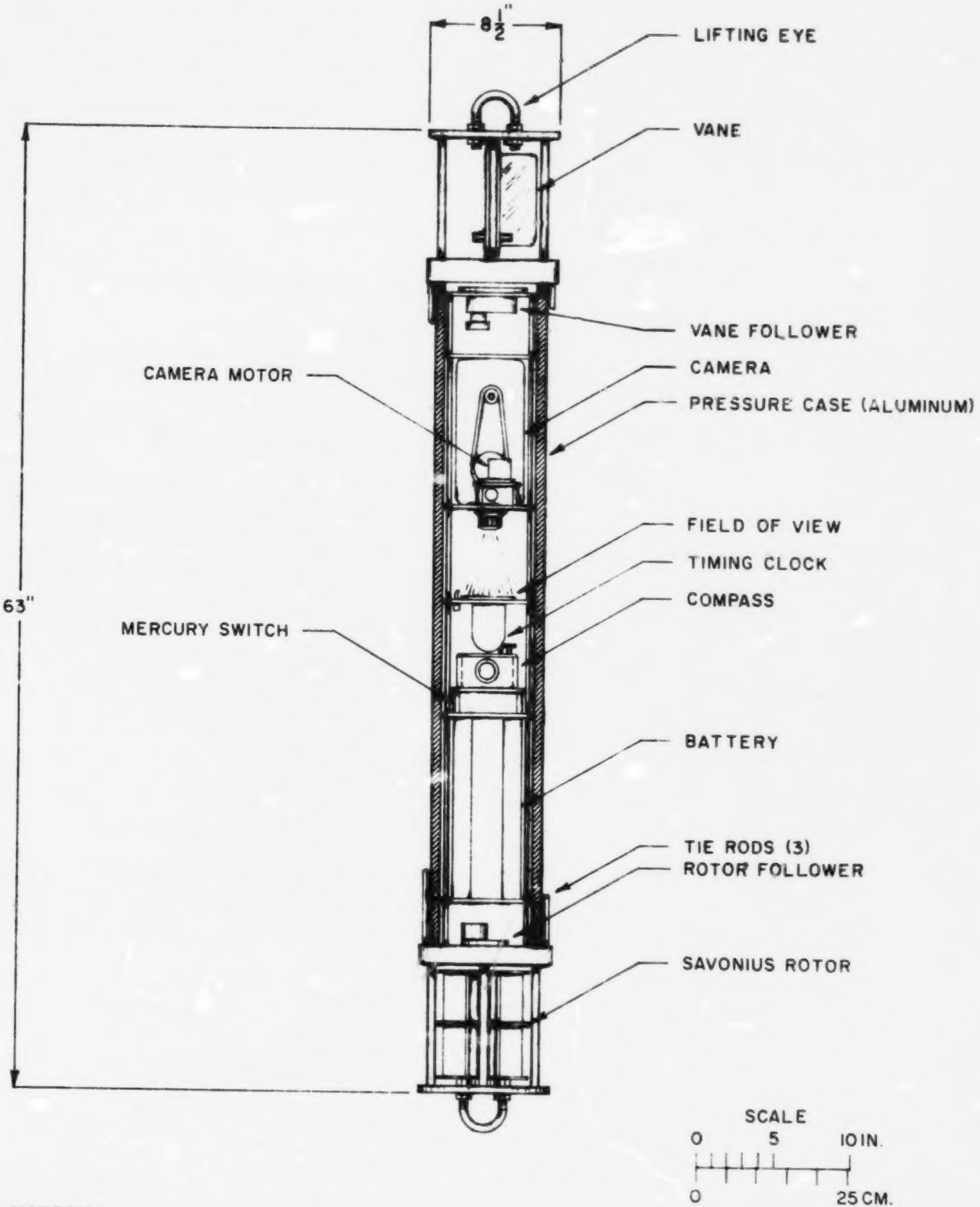
FINISH
OXIDE FINISH & YELLOW EPOXY PAINT
ON ALUMINUM PARTS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TEMPERATURE RECORDER

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois

FIGURE 4 -7


8½"
LIFTING EYE
VANE
VANE FOLLOWER
CAMERA MOTOR
CAMERA
PRESSURE CASE (ALUMINUM)
FIELD OF VIEW
TIMING CLOCK
COMPASS
63"
MERCURY SWITCH
BATTERY
TIE RODS (3)
ROTOR FOLLOWER
SAVONIUS ROTOR
SCALE
0 5 10 IN.
0 25 CM.

MATERIAL

ALUMINUM & STAINLESS STEEL

FINISH

OXIDE FINISH & YELLOW EPOXY PAINT
ON ALUMINUM PARTS

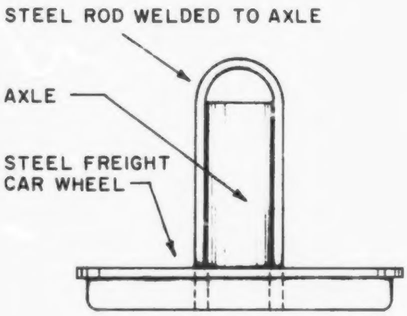
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

CURRENT METER

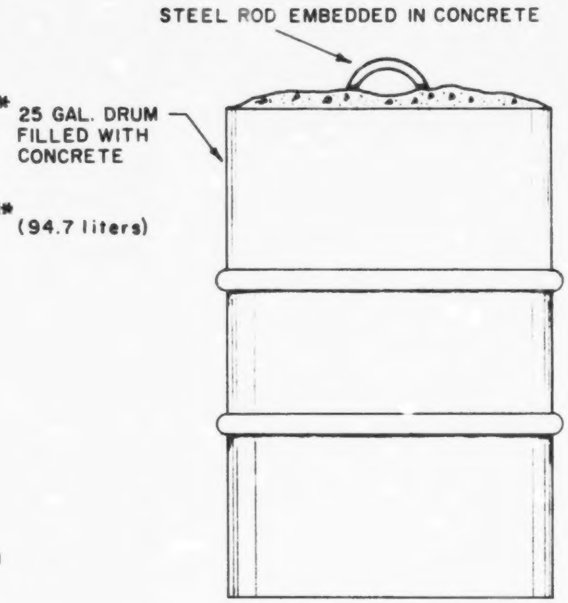
WOODS HOLE TYPE

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-8


STEEL ROD WELDED TO AXLE
AXLE
STEEL FREIGHT CAR WHEEL

850 LB. WHEEL ANCHOR
(362 Kg.)


STEEL ROD EMBEDDED IN CONCRETE
* 25 GAL. DRUM FILLED WITH CONCRETE
* (94.7 liters)

225 LB. DRUM ANCHOR
(100 Kg.)

MATERIAL
AS SHOWN

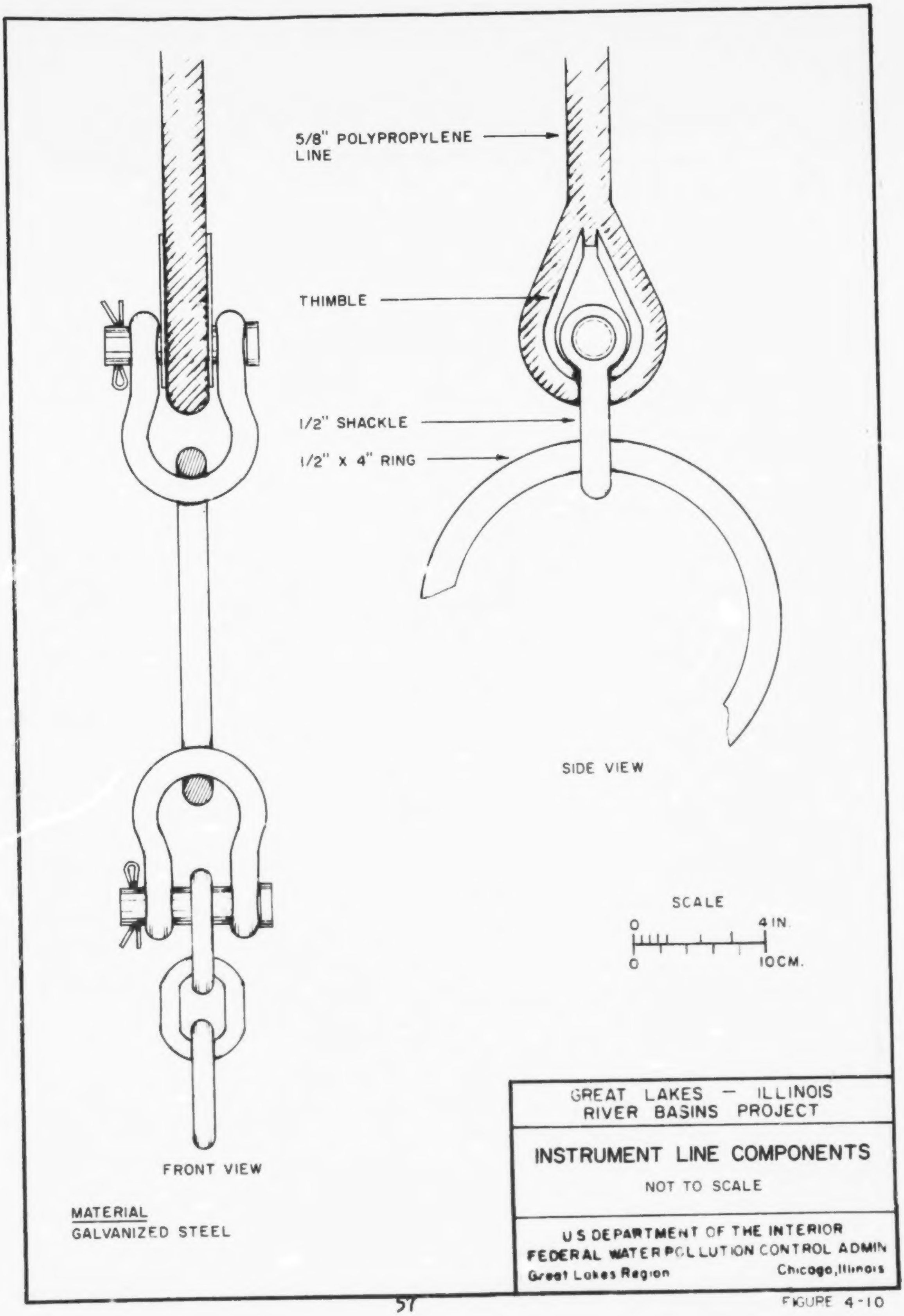
GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

ANCHORS

NOT TO SCALE

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-9


5/8" POLYPROPYLENE LINE
THIMBLE
1/2" SHACKLE
1/2" x 4" RING
SIDE VIEW
SCALE
0
4 IN.
0
10CM.
FRONT VIEW

MATERIAL
GALVANIZED STEEL

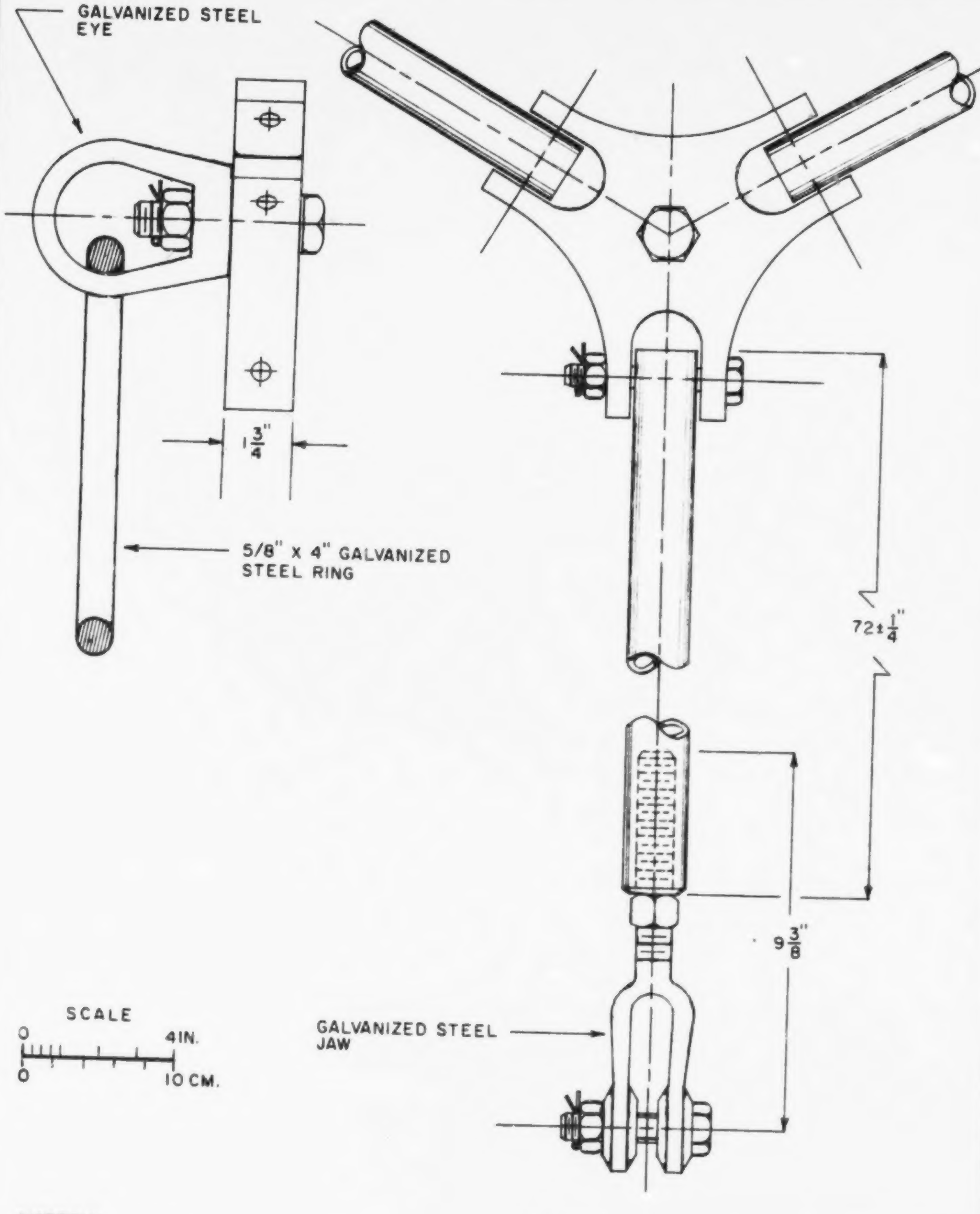
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

INSTRUMENT LINE COMPONENTS

NOT TO SCALE

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 4-10


GALVANIZED STEEL EYE
1 3/4"
5/8" X 4" GALVANIZED STEEL RING
72 ± 1/4"
9 3/8"
GALVANIZED STEEL JAW
SCALE
0
4 IN.
0
10 CM.

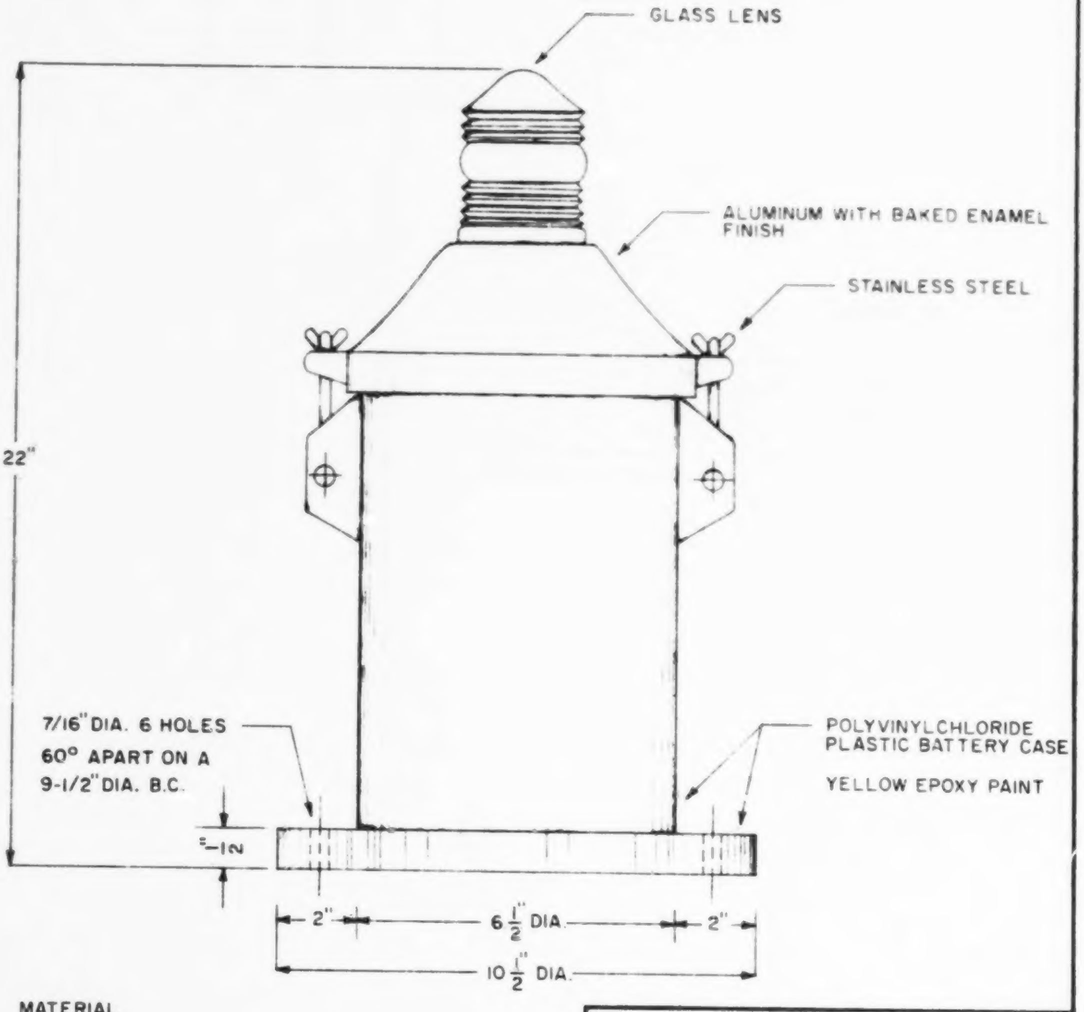
MATERIAL
STAINLESS STEEL

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

RIGID BRIDLE
NOT TO SCALE

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 4-11


GLASS LENS
ALUMINUM WITH BAKED ENAMEL FINISH
STAINLESS STEEL
22"
7/16" DIA. 6 HOLES
60° APART ON A
9-1/2" DIA. B.C.
1 IN
POLYVINYLCHLORIDE
PLASTIC BATTERY CASE
YELLOW EPOXY PAINT
2"
6 1/2" DIA.
2"
10 1/2" DIA.

MATERIAL
AS SHOWN

FINISH
AS SHOWN

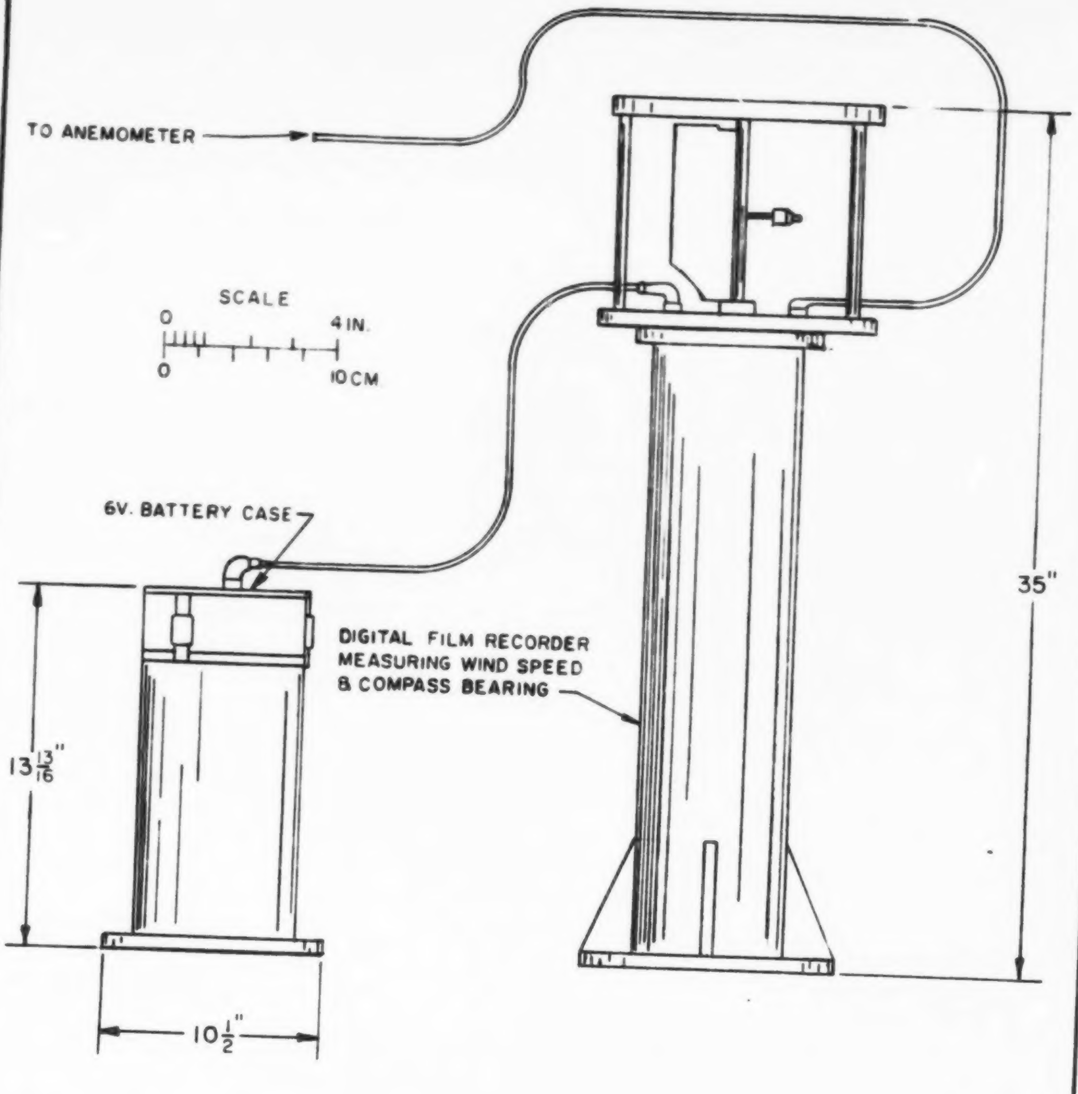
SCALE
0 4 IN.
0 10 CM.

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

NAVIGATION LIGHT
NOT TO SCALE

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 4-12

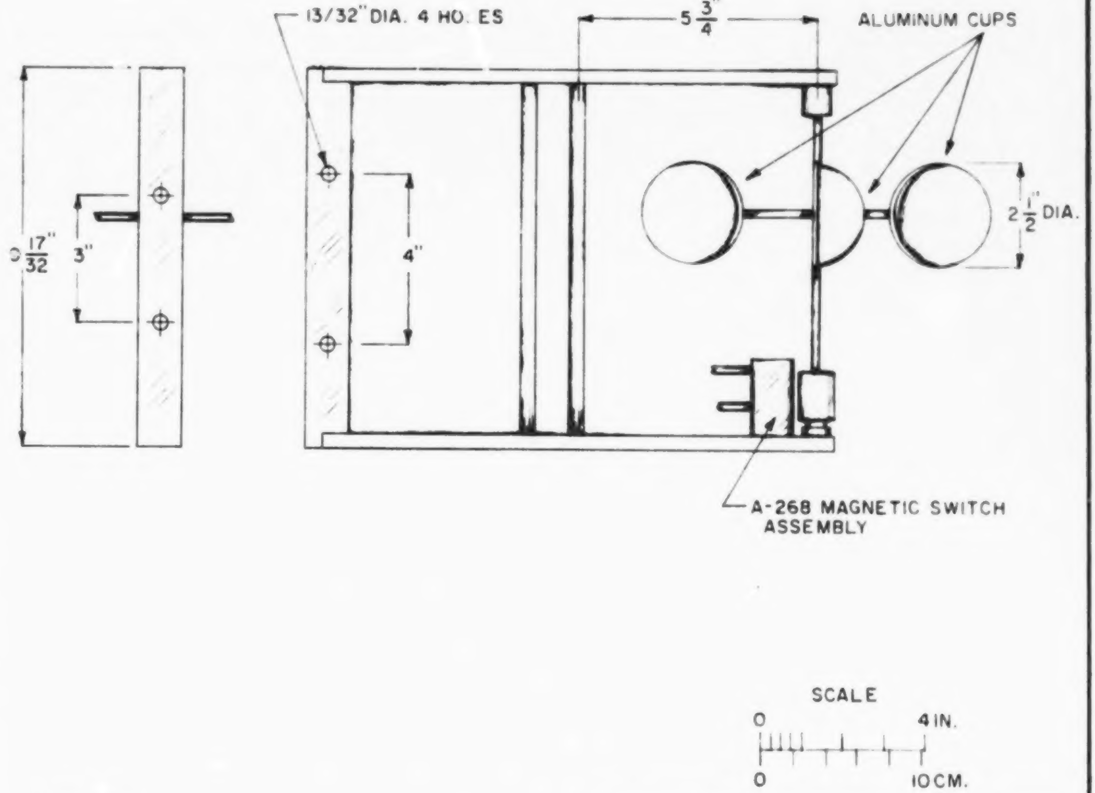

TO ANEMOMETER
SCALE
0
4 IN.
0
10 CM
6V. BATTERY CASE
DIGITAL FILM RECORDER MEASURING WIND SPEED & COMPASS BEARING
35"
13 13/16"
10 1/2"

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND RECORDER

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-13


13/32" DIA. 4 HOLES
5 3/4"
ALUMINUM CUPS
9 17/32"
3"
4"
2 1/2" DIA.
A-268 MAGNETIC SWITCH ASSEMBLY
SCALE
0
4 IN.
0
10CM.

MATERIAL

ALUMINUM WITH STAINLESS STEEL FASTENERS

FINISH

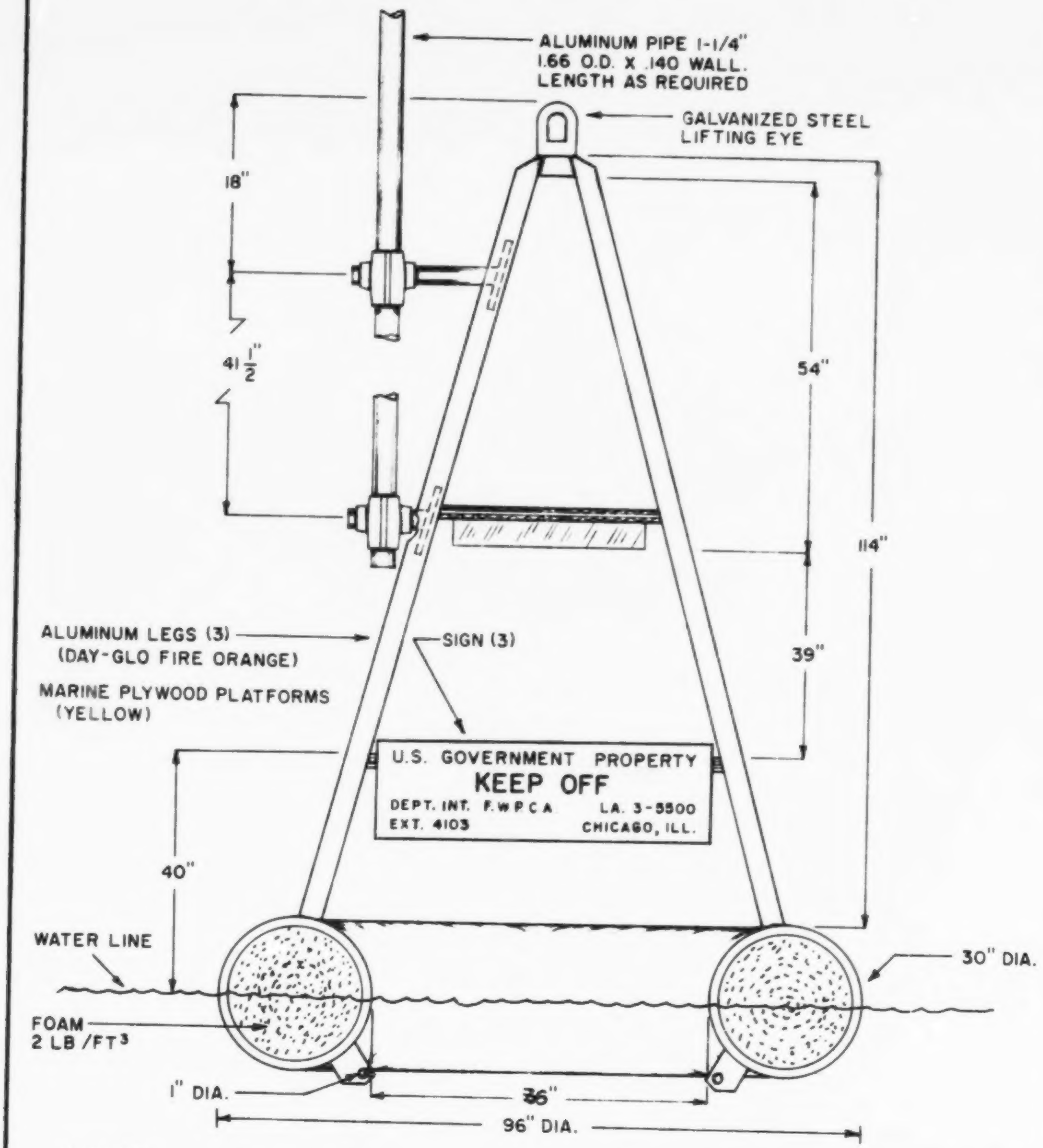
BLACK ANODIZE FINISH ON ALUMINUM CUPS

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

HEAVY DUTY ANEMOMETER

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region **Chicago, Illinois**

FIGURE 4-14


ALUMINUM PIPE 1-1/4"
1.66 O.D. X .140 WALL.
LENGTH AS REQUIRED
GALVANIZED STEEL
LIFTING EYE
18"
41 1/2"
54"
114"
39"
ALUMINUM LEGS (3)
(DAY-GLO FIRE ORANGE)
SIGN (3)
MARINE PLYWOOD PLATFORMS
(YELLOW)
U.S. GOVERNMENT PROPERTY
KEEP OFF
DEPT. INT. F.W.P.C.A.
LA. 3-5500
EXT. 4103
CHICAGO, ILL.
40"
WATER LINE
30" DIA.
FOAM
2 LB/FT³
1" DIA.
36"
96" DIA.

MATERIAL
AS SHOWN

FINISH
AS SHOWN

SCALE
0 4 IN.
0 10 CM.

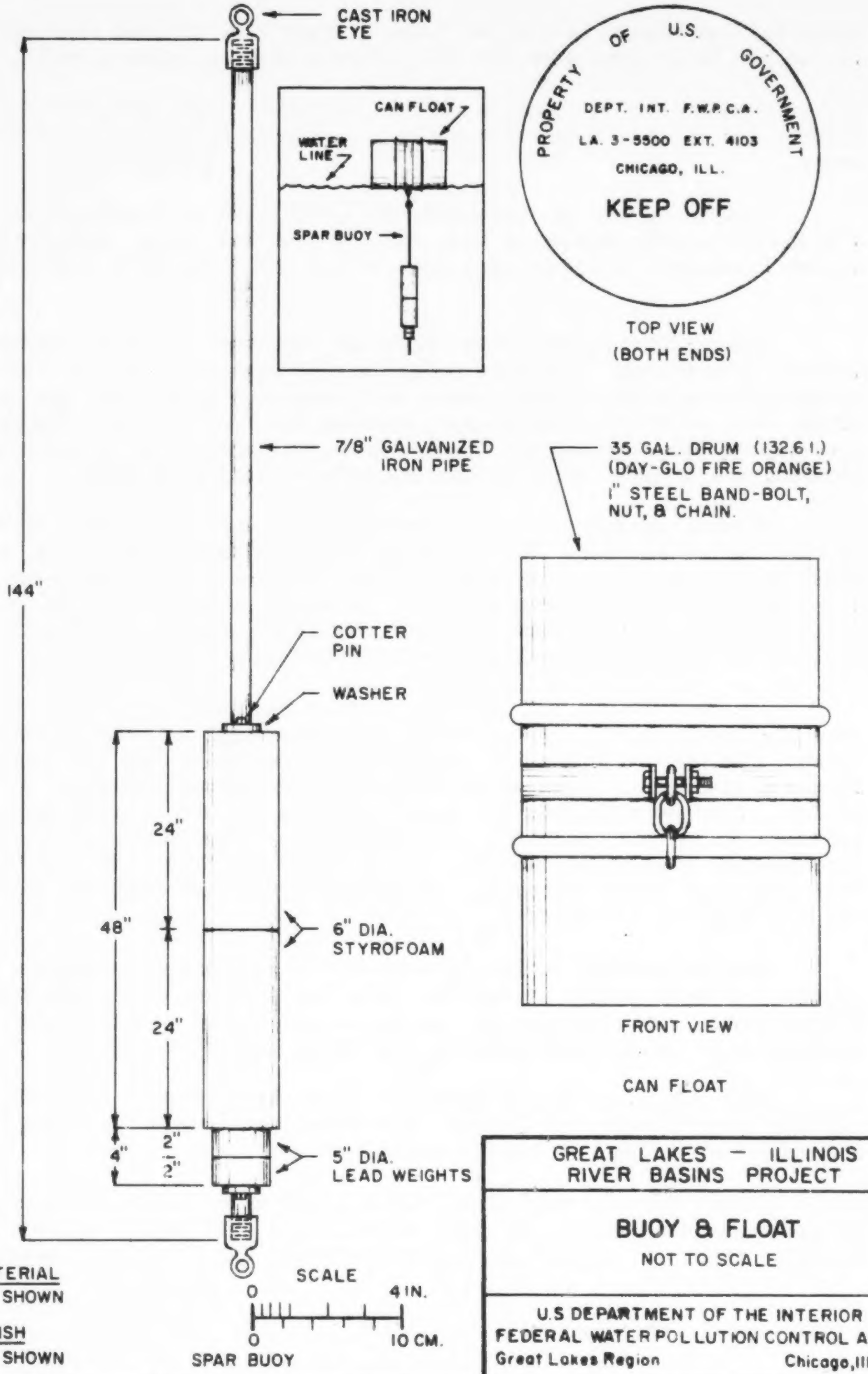
NOTE
PAINT LEGS & BUOY DAY-GLO FIRE ORANGE
WITH CLEAR ANTI-FADE FINISH COAT.

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

INSTRUMENT BUOY
TOROIDAL SHAPE
NOT TO SCALE

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 4-15


CAST IRON EYE
CAN FLOAT
WATER LINE
SPAR BUOY
PROPERTY OF U.S. GOVERNMENT
DEPT. INT. F.W.P.C.A.
LA. 3-5500 EXT. 4103
CHICAGO, ILL.
KEEP OFF
TOP VIEW
(BOTH ENDS)
7/8" GALVANIZED IRON PIPE
35 GAL. DRUM (132.6 l.)
(DAY-GLO FIRE ORANGE)
1" STEEL BAND-BOLT, NUT, & CHAIN.
144"
COTTER PIN
WASHER
24"
48"
6" DIA. STYROFOAM
24"
FRONT VIEW
CAN FLOAT
2"
4"
2"
5" DIA. LEAD WEIGHTS
SCALE
0
4 IN.
0
10 CM.
SPAR BUOY

MATERIAL
AS SHOWN

FINISH
AS SHOWN

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

BUOY & FLOAT

NOT TO SCALE

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-16

water and the anchor is dropped. The surface buoy is then launched and its anchor is dropped when the line between anchors becomes taut.

Retrieval of a station array is simple and consists of first lifting the surface buoy followed by the remainder of the array in order.

A winter array is launched and retrieved in a similar manner. A lighter concrete anchor is used for the surface buoy part of the system in winter, since it must moor only a small recovery buoy (Figure 4-3).

Some difficulties were expected in the mooring system and several have arisen. The main problems have been in the instrumented surface buoy mooring. Apparently, the mooring line near the anchor often was abraded by the anchor, setting the buoy adrift. Polypropylene rope, used because of its strength, buoyancy, and resistance to chemical and organic decay is, unfortunately, easily abraded.

Another problem with the surface buoy has been that it would capsize during storms. The buoy is just as stable inverted as right side up. Chain in the mooring line lessened the frequency of this occurrence but did not eliminate it. It became a major problem in Lake Erie because of short steep waves in shallower water. It finally was overcome by placing a 3-m length of railroad rail in the mooring line.

A weak link was put into the surface buoy mooring line to eliminate the possibility of breaking the mooring line when pulling the anchor. In Lake Michigan the weak link worked well, but in Lake Erie it was unsuccessful apparently due to high frequency stresses of wave action. Consideration had not been given to the results of weak link breakage while the stations were unattended. When breakage occurred, the surface buoy was then anchored to the meter by a very long line. This line then wound around the instrument array, the line was abraded, and the buoy was set adrift.

A major problem in the work on Lake Michigan was inadequate navigation. Losses due to navigation have not occurred since the vessel, Telson Queen, was contracted as the survey vessel. This vessel was equipped with radar, gyro compass, and radio direction finder.

Some equipment and/or data have been lost because of vandalism, passing ship damage, ice damage, corrosion, wave hammering, and array assembly errors. All of these losses were relatively minor.

Except for the weak links, there have been no failures because of exceeding the working strength of materials. Tables 4-1 and 4-2 list the more important specifications of equipment which apply to mooring.

TABLE 4-1

SPECIFICATIONS OF METERING EQUIPMENT

Item	Buoyancy		Maximum Operating Depth (M)	Construction	Tension Strength	
	Kg	Lbs			Kg	Lbs
Surface buoy	2,270	5,000	-	Fiberglass-wrapped styrofoam	3,178	7,000
Recovery buoy	36	80	18	Fiberglass-wrapped styrofoam	-	-
Subsurface buoy	227	500	18	Fiberglass-wrapped styrofoam	6,810	15,000
Current meter	-13.6	-30	2,700	Aluminum and stainless steel	2,270	5,000
Temperature recorder	-2.3	-5	1,350	Aluminum and stainless steel	3,600	8,000
Recovery Inst.	-4.5	-10	1,350	Aluminum and stainless steel	1,816	4,000

TABLE 4-2

SPECIFICATIONS OF MOORING MATERIALS

Item	Construction	Working Strength		Use
		Kg	Lbs	
½" rope(1.2 cm)	Polypropylene	1,362	3,000	Weak link.
3/4" rope(1.9 cm)	Polypropylene	2,724	6,000	Anchor line.
3/8" chain(9.6 cm)	Galv. steel	1,362	3,000	Anchor line.
7/16" shackle(1.1 cm)	Galv. steel	1,135	2,500	Chain connection.
½" shackle (1.2 cm)	Galv. steel	1,816	4,000	Line and instrumen connection.
3/4" shackle(1.9 cm)	Galv. steel	4,086	9,000	Anchor connection.
½" ring(1.2 cm)	Galv. steel	2,724	6,000 (yield)	Current meter lin connection.
5/8" ring(1.6 cm)	Galv. steel	3,178	7,000 (yield)	Anchor line surface buoy.
5/8" braid(1.6 cm)	Polypropylene	2,724	6,000	Instrument line.
7/16" braid(1.1 cm)	Dacron and nylon	2,724	6,000	Recovery buoy line.

When a station was recovered the station diagram was used to recheck the various pieces of equipment used and all corrections noted on the same sheet. Damaged rotors, vanes, or other items were listed. The instruments were returned to the shop and a complete check made on various components and entered against the instrument maintenance log. When the current meter films were removed they were placed in a metal container and the instrument serial number was taped to the container. Later, a film log sheet (Table 4-3) was filled in, assigning permanent film serial numbers to each record. The film series 200 000 has been assigned to the Great Lakes. This has been further subdivided as follows:

200 000	Lake Michigan
210 000	Lake Erie
220 000	Lake Ontario
230 000	Lake Huron
240 000	Lake Superior

The film log sheet was filled in and shipped with the film to a film reading agency where the records are filed and the films are sent for processing.

The Inspection Sheets, Tables 4-4, 4-5, and 4-6, were used both before and after each use. A file was kept on each instrument with its performance and maintenance background. Proper inspection insures that data are reliable.

Film Processing

Eastman Kodak, 16 mm, double X, panchromatic, negative movie film, DXN 449, on 30 m (100') daylight loading reels was used in the current meter camera (Figure 4-17). The exposed film was delivered to the processing contractor on 30 m reels in blacktape-sealed cans in the original yellow boxes which have been marked in accordance with the user's own identification and numbering information.

Upon receipt of the film the contractor perforated an identifying number or code on the tail of each roll and on the flap of the yellow box from which it was taken. The film was "tail out" on the reel.

All films from a single order were then spliced together head to tail for processing. This processing was described as "Extended Processing."

A positive print was then made of the original film on fine grain release film using emulsion-to-emulsion contact for maximum

TABLE 4-3

16 mm Film Data
IDENTIFICATION SHEET
AND LOG

Date________________________

Film Serial No.________________ Emulsion No.________________

Type of Inst.________________ Serial No.________________

Date/Time Started________________ Station No.________________

Date/Time Ended________________ Depth________________

Speed of Film (Cont.)________________ Time (Interval)________________

Lat.:________________ Long.:________________

Lake________________ Job:________________

Beginning Ft. Mark________________ Frames Skipped________________

Batch No.________________

Processing Neg.________________ Positive__________Quantity__________

Edge No.'s Original________________ Prints________________

Original Stored________________________________

1st Print Stored________________________________

Film to be read

Continuous________________ Interval________________

Recovery Buoy #________________ Temperature Recorder #________________

Wind Recorder #________________

Sfc. Temp. Recorder #________________

Copy

______Geodyne

______University of Wisconsin

______Permanent File

______Other Files

TABLE 4-4a

INSPECTION SHEET-CURRENT METERS TEAR-DOWN

1. STROBE
   a. ____ Seconds
   b. ____ Board and components
   c. ____ Elect. connections
   d. ____ Cont. and strobe lights
   e. ____ Operational check
2. CLOCK
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational
   d. ____ Timed
   e. ____ Cam
3. MOTOR
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational
   d. ____ Timed
   e. ____ Gear and shaft
   f. ____ RPM
4. MOTOR SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational check
5. CLOCK SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Arm adjustment
   d. ____ Operational check
6. MERC. SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Functional check
7. POWER SWITCH
   a. ____ Secure
   b. ____ Functional Check
   c. ____ Elect. connections
8. BATTERY
   a. ____ Secure - no leakage
   b. ____ Voltage
9. BATTERY CONNECTOR
   a. ____ Elect. connections
   b. ____ Clean
   c. ____ Resistance check
10. CAMERA
    a. ____ Secure
    b. ____ Lens tight
    c. ____ Lens' setting
    d. ____ Drive engaged
    e. ____ Pulley and rubber
    f. ____ Film record (L, S, N)
11. VANE
    a. ____ Clean
    b. ____ Magnets
    c. ____ Bearings
    d. ____ Adjustments
    e. ____ Free rotation
    f. ____ No visual damage
12. VANE FOLLOWER
    a. ____ Secure
    b. ____ Leakage
    c. ____ Bubbles
    d. ____ No binding
    e. ____ Disc alignment
    f. ____ Lite
    g. ____ Lite pipes
    h. ____ Viscosity
    i. ____ Diaphram
13. ROTOR
    a. ____ Clean
    b. ____ Magnets
    c. ____ Bearings
    d. ____ Free rotation
    e. ____ No visual damage
14. ROTOR FOLLOWER
    a. ____ Secure
    b. ____ Elect. connections
    c. ____ I-I lite
    d. ____ IO-I lite
    e. ____ Lite pipes
15. COMPASS
    a. ____ Secure
    b. ____ Leakage
    c. ____ Bubbles
    d. ____ No binding
    e. ____ Disc alignment
    f. ____ Lite
    g. ____ Lite pipes
    h. ____ Diaphram
16. READ PULSE
    a. ____ Secure
    b. ____ Elect. connections
    c. ____ Lite
    d. ____ Lite pipe
17. FRAME AND HARDWARE
    a. ____ Clean
    b. ____ Secure
18. "O" RINGS
    a. ____ Seats undamaged
    b. ____ No leakage
19. OPERATIONAL CHECK
    a. ____ Advance of film
    b. ____ With film removed
20. POWER SWITCH
    a. ____ Continuous
    b. ____ Off
    c. ____ Interval
21. CASE
    a. ____ No visual damage
22. EXTERIOR BOLTS
    a. ____ Tight
23. DATE
    a. ____ Open

TABLE 4-4b

INSPECTION SHEET-CURRENT METERS BUILD-UP

1. STROBE
   a. ____ Seconds
   b. ____ Board and components
   c. ____ Elect. connections
   d. ____ Cont. and strobe lights
   e. ____ Operational check
2. CLOCK
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Rewind
   d. ____ Timed
   e. ____ Cam
3. MOTOR
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Brushes cleaned
   d. ____ Timed
   e. ____ Gear and shaft
   f. ____ RPM
4. MOTOR SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational check
5. CLOCK SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Arm adjustment
   d. ____ Operational check
6. MERC. SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Functional check
7. POWER SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Functional check
8. BATTERY
   a. ____ Secure
   b. ____ Voltage
9. BATTERY CONNECTOR
   a. ____ Elect. connections
   b. ____ Clean
   c. ____ Resistance check
10. CAMERA
    a. ____ Secure
    b. ____ Clean
    c. ____ Lens' setting
    d. ____ Drive engaged
    e. ____ Pulley and rubber
    f. ____ Film loaded
11. VANE
    a. ____ Clean
    b. ____ Magnets
    c. ____ Bearings
    d. ____ Adjustments
    e. ____ No visual damage
    f. ____ Free rotation
12. VANE FOLLOWER
    a. ____ Secure
    b. ____ Leakage
    c. ____ Bubbles
    d. ____ No binding
    e. ____ Disc alignment
    f. ____ Lite
    g. ____ Lite pipes
    h. ____ Viscosity
    i. ____ Diaphram
13. ROTOR
    a. ____ Clean
    b. ____ Magnets
    c. ____ Bearings
    d. ____ Free rotation
    e. ____ No visual damage
14. ROTOR FOLLOWER
    a. ____ Secure
    b. ____ Elect. connections
    c. ____ I-I lites
    d. ____ IO-I lites
    e. ____ Lite pipes
15. COMPASS
    a. ____ Secure
    b. ____ Leakage
    c. ____ Bubbles
    d. ____ No binding
    e. ____ Disc alignment
    f. ____ Lite
    g. ____ Lite pipes
    h. ____ Diaphram
16. READ PULSE
    a. ____ Secure
    b. ____ Elec. connections
    c. ____ Lite
    d. ____ Lite pipes
17. IDENTIFICATION
    a. ____ Ser. no. on outside case
    b. ____ Type of cam (lobes)
18. "O" RINGS
    a. ____ Seat clean
    b. ____ Properly seated
19. OPERATIONAL CHECK
    a. ____ Without film
    b. ____ With film
20. POWER SWITCH POSITION
    a. ____ Continuous
    b. ____ Off
    c. ____ Interval
21. DESSICANT
    a. ____ Installed
22. EXTERIOR BOLTS
    a. ____ Torqued
23. DATE
    a. ____ Open
    b. ____ Closed

TABLE 4-5a

INSPECTION SHEET - TEMPERATURE RECORDER TEAR-DOWN

1. GENERAL EXTERIOR
    a. ____ Exterior clean, no damage to case or end plates
    b. ____ Case properly seated
    c. ____ Tie rod nuts drawn up tight
    d. ____ Tie rod nuts, washers and end plates removed
    e. ____ No damage to case sealing surfaces
2. GENERAL INTERIOR
    a. ____ Clock operating - note switch position
    b. ____ Battery voltage checked (record reading)
    c. ____ Graph tracking on spool (indicate end and date on graph)
    d. ____ Indicate length of graph as: long, short, none, normal
    e. ____ Operational check (indicate type of cam)
3. TEMPERATURE SENSOR
    a. ____ Sensor and components secure
    b. ____ Scribe tracking and secured to shaft
    c. ____ Sensor spiral free, no corrosion
    d. ____ Calibration check (record results)
    e. ____ Stops on slide bar properly positioned
    f. ____ Graph removed and identified as to serial number and date opened
4. SPOOLS
    a. ____ Spools and shafts free and clean, restraining clips secure
    b. ____ Check spring tension of shafts
    c. ____ Face plate smooth and clean
5. CLOCK MOUNT
    a. ____ Mount bracket secure
    b. ____ Electrically isolated from frame
    c. ____ Air gap between bracket and power switch
    d. ____ Clock secure on bracket
6. CLOCK
    a. ____ Elect. connections.
    b. ____ Rewind (check and record timing)
    c. ____ Clock micro switch secure and operational
7. MOTOR SWITCH
    a. ____ Secured
    b. ____ Elect. connections
    c. ____ Functional check
8. MERC. SWITCH
    a. ____ Secure
    b. ____ Functional check
9. POWER SWITCH
    a. ____ Elect. connection
    b. ____ Functional check
10. MOTOR AND MOUNT
    a. ____ Elect. connections
    b. ____ Functional check
    c. ____ Timed
    d. ____ Gear and shaft secure
    e. ____ No binding of gear-train
    f. ____ Motor and mount secure
11. GENERAL
    a. ____ Removed battery
    b. ____ Battery leads checked
    c. ____ Starting at base all hardware secured
    d. ____ No evidence of corrosion
    e. ____ "O" ring grooved free of nicks, burrs, or dirt
    f. ____ Instrument clean and rotating parts lubricated

TABLE 4-5b

INSPECTION SHEET - TEMPERATURE RECORDER BUILD-UP
(WITH UTILITY BATTERY INSTALLED)

12. MOTOR
    a. ____ Brushes and armature cleaned and free
    b. ____ Gov. points cleaned and adjusted
    c. ____ Leads properly soldered and routed with no strain
    d. ____ No visible damage to housing; shaft and gear secure
    e. ____ With motor disengaged, gear-train movement free
    f. ____ Micro switch secure and operational (leads properly routed)
    g. ____ Motor gear properly meshed with gear-train
    h. ____ Motor and mount secured to instrument
    i. ____ Operational and time check
13. CLOCK
    a. ____ Installed, check arming and timing
    b. ____ Leads secure with no damage or strain
    c. ____ Adequate clearance between elect. connector and motor
    d. ____ Mount bracket isolated from frame and power switch
    e. ____ Cam installed (indicate number of lobes)
14. CLOCK MICRO SWITCH
    a. ____ Switch installed
    b. ____ Leads properly soldered and routed with no strain
    c. ____ Verify routing of leads to other components
    d. ____ Actuator arm adjusted
    e. ____ Functional check
15. TEMPERATURE SENSOR
    a. ____ Sensor and components secured
    b. ____ Sensor spiral free and no corrosion
    c. ____ No evidence of transfer fluid leakage
    d. ____ No damage or improper routing of transfer tube
    e. ____ Scribe secured to shaft and indicating approx. temp.
    f. ____ Face plate smooth and clean
    g. ____ Spool shaft bushings clean and lubricated
    h. ____ Shaft locking clips secure with free movement
16. SPOOLS
    a. ____ Free and clean
    b. ____ Shafts clean and proper spring tension
    c. ____ Test tape installed, scribe adjusted
    d. ____ Operational test (2-3 weeks) completed
17. CALIBRATION
    a. ____ Install new tape, verify hole and sprocket alignment
    b. ____ Calibrate instrument (indicate range)
18. BATTERY
    a. ____ Voltage (note on tape ser. no., date, and starting point)
    b. ____ Operational check performed
19. "O" RINGS
    a. ____ Case clean, sealing surfaces free of damage or dirt
    b. ____ "O" rings installed in base and cover
20. POWER SWITCH
    a. ____ Continuous
    b. ____ Off
    c. ____ Interval
21. DESSICANT
    a. ____ Installed
22. CASE
    a. ____ Case and cover - tie rods installed and nuts torqued
    b. ____ Instrument identified with ser. no. and type of cam

TABLE 4-6a

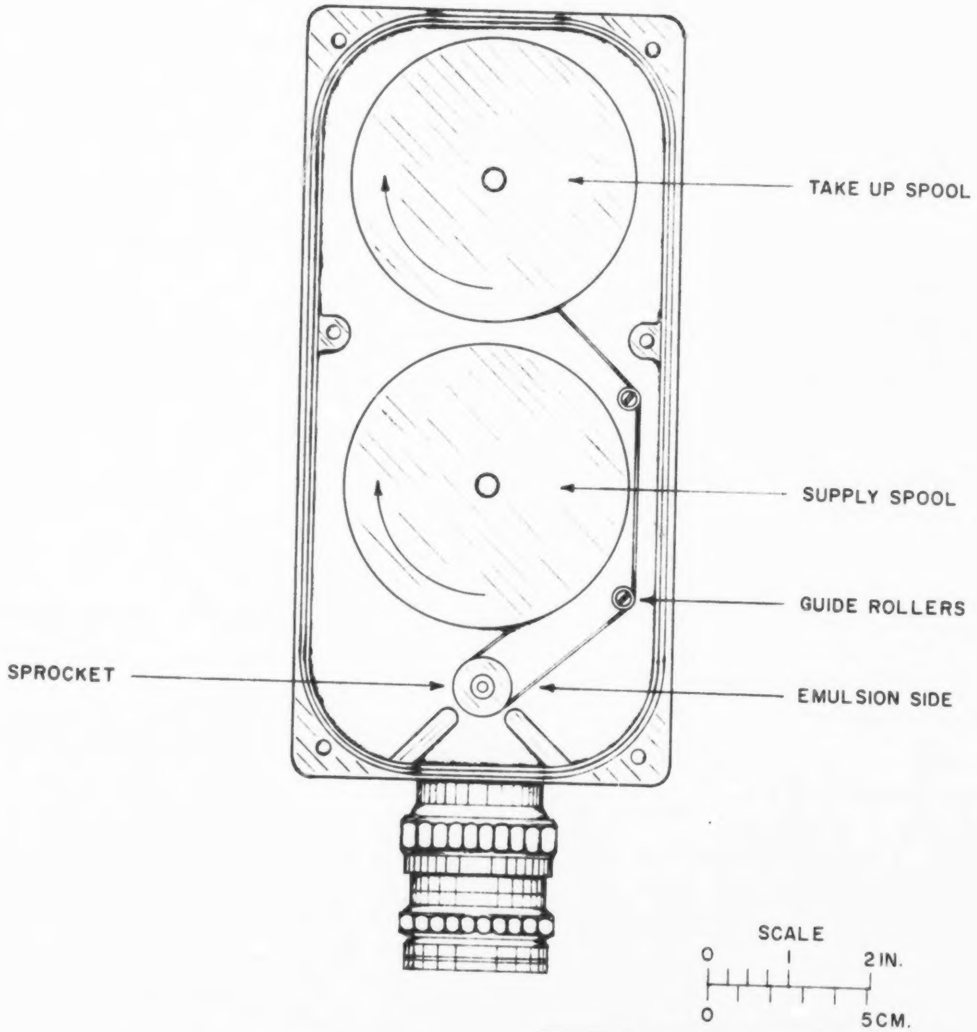
INSPECTION SHEET-WIND RECORDER TEAR-DOWN

1. STROBE
   a. ____ Seconds
   b. ____ Board and components
   c. ____ Elect. connections
   d. ____ Cont. and strobe lights
   e. ____ Operational check
2. CLOCK
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational
   d. ____ Timed
   e. ____ Cam
3. MOTOR
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational check
   d. ____ Timed
   e. ____ Gear and shaft
   f. ____ RPM
4. MOTOR SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational check
5. CLOCK SWITCH
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Arm adjustment
   d. ____ Operational check
6. BATTERY CASE
   a. ____ Clean
   b. ____ Cover fasteners secure
   c. ____ No visible damage
7. POWER
   a. ____ Secure
   b. ____ Elect. connections
   c. ____ Operational check
8. BATTERY
   a. ____ Secure, no leakage
   b. ____ Voltage
9. BATTERY CONNECTOR
   a. ____ Elect. connections
   b. ____ Clean
   c. ____ Resistance check
10. CAMERA
    a. ____ Secure
    b. ____ Lens tight
    c. ____ Lens' setting
    d. ____ Drive engaged
    e. ____ Pulley and rubber
    f. ____ Film record (L,S,N)
11. VANE
    a. ____ Clean
    b. ____ Magnets
    c. ____ Bearings
    d. ____ Adjustments
    e. ____ Free rotation
    f. ____ No visible damage
12. VANE FOLLOWER
    a. ____ Secure
    b. ____ Leakage
    c. ____ Bubbles
    d. ____ No binding
    e. ____ Disc alignment
    f. ____ Lite
    g. ____ Lite pipes
    h. ____ Viscosity
    i. ____ Diaphram
13. ANEMOMETER
    a. ____ Frame secure
    b. ____ Pickup and leads checked
    c. ____ Bearings and free rotation
    d. ____ Cups and shaft secure
    e. ____ Operational check
14. BOARD AND LITES
    a. ____ Board and lites secure
    b. ____ Elect. connections
    c. ____ I-I lite
    d. ____ IO-I lite
    e. ____ Lite pipes
15. COMPASS
    a. ____ Secure
    b. ____ Leakage
    c. ____ Bubbles
    d. ____ No binding
    e. ____ Disc alignment
    f. ____ Lite
    g. ____ Lite pipes
    h. ____ Diaphram
16. READ PULSE
    a. ____ Secure
    b. ____ Elect. connections
    c. ____ Lite
    d. ____ Lite pipe
17. FRAME AND HARDWARE
    a. ____ Clean
    b. ____ Secure
18. "O" RINGS
    a. ____ Seats undamaged
    b. ____ No leakage
19. OPERATIONAL CHECK
    a. ____ Film advance
    b. ____ With film removed
20. POWER SWITCH
    a. ____ Continuous
    b. ____ Off
    c. ____ Interval
21. CASE
    a. ____ No visible damage
22. EXTERIOR HARDWARE
    a. ____ Secure
23. DATE
    a. ____ Open

TABLE 4-6b

INSPECTION SHEET-WIND RECORDER BUILD-UP

1. STROBE
a. ____ Seconds
b. ____ Board and components
c. ____ Elect. connections
d. ____ Cont. and strobe lights
e. ____ Operational check
2. CLOCK
a. ____ Secure
b. ____ Elect. connections
c. ____ Rewind
d. ____ Timed
e. ____ Cam
3. MOTOR
a. ____ Secure
b. ____ Elect. connections
c. ____ Brushes cleaned
d. ____ Timed
e. ____ Gear and shaft
f. ____ RPM
4. MOTOR SWITCH
a. ____ Secure
b. ____ Elect. connections
c. ____ Operational check
5. CLOCK SWITCH
a. ____ Secure
b. ____ Elect. connections
c. ____ Arm adjustment
d. ____ Operational check
6. BATTERY CASE
a. ____ No visible damage
b. ____ Cover fasteners secure
c. ____ Clean
7. POWER SWITCH
a. ____ Secure
b. ____ Elect. connections
c. ____ Functional check
8. BATTERY
a. ____ Secure
b. ____ Voltage
9. BATTERY CONNECTOR
a. ____ Elect. connections
b. ____ Clean
c. ____ Resistance check
10. CAMERA
a. ____ Secure
b. ____ Clean
c. ____ Lens' setting
d. ____ Drive engaged
e. ____ Pulley and rubber
f. ____ Film loaded
11. VANE
a. ____ Clean
b. ____ Magnets
c. ____ Bearings
d. ____ Adjustment
e. ____ Free rotation
f. ____ No visible damage
12. VANE FOLLOWER
a. ____ Secure
b. ____ Leakage
c. ____ Bubbles
d. ____ No binding
e. ____ Disc alignment
f. ____ Lite
g. ____ Lite pipes
h. ____ Viscosity
i. ____ Diaphram
13. ANEMOMETER
a. ____ Frame secure
b. ____ Pickup and leads checked
c. ____ Bearings and free rotation
d. ____ Cups and shaft secure
e. ____ Operational check
14. BOARD AND LITES
a. ____ Board and lites secure
b. ____ Elect. connections
c. ____ I-I lite
d. ____ IO-I lite
e. ____ Lite pipes
15. COMPASS
a. ____ Secure
b. ____ Leakage
c. ____ Bubbles
d. ____ No binding
e. ____ Disc alignment
f. ____ Lite
g. ____ Lite pipes
h. ____ Diaphram
16. READ PULSE
a. ____ Secure
b. ____ Elect. connections
c. ____ Lite
d. ____ Lite pipes
17. IDENTIFICATION
a. ____ Ser. no. on outside
b. ____ Type of cam (lobes)
18. "O" RINGS
a. ____ Seat clean
b. ____ Properly seated
19. OPERATIONAL CHECK
a. ____ Without film
b. ____ With film
20. POWER SWITCH POSITION
a. ____ Continuous
b. ____ Off
c. ____ Interval
21. DESSICANT
a. ____ Installed
22. EXTERIOR BOLTS
a. ____ Torqued
23. DATE
a. ____ Closed


TAKE UP SPOOL
SUPPLY SPOOL
GUIDE ROLLERS
SPROCKET
EMULSION SIDE
SCALE
0
1
2 IN.
0
5 CM.

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

CAMERA LOADING DIAGRAM

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 4-17

clarity of reproduction. Due to this, the print and the original were mirror images of each other as viewed from the same, such as the emulsion, side. For reference it should be noted here that the original film, when viewed from the emulsion side with the beginning (head) end to the right, concluding (tail) end to the left, had the continuous channel on top.

After developing the original and making the positive print, both were edge-numbered serially using a common starting point for complete coincidence. The numbering proceeded from the head of the first 30 m consecutively increasing throughout those spliced together to the tail of the last. The four digit number (0000 to 9999) was preceded by one of the following letters according to the user's choice: A, B, C, D, E, F, G, H, J.

The original film was then broken down, rewound head out on the original spools and returned to the original boxes.

The prints were broken down and rewound head out on individual 30 m reels and boxes. These boxes are marked according to the perforations made in the original film and the user's number as it appeared on the original yellow box. The prints were then returned according to instructions.

Following the processing the exposed film was returned to the reading agency and the length of record determined as well as other information pertaining to the record.

The clear-edged prints were visually viewed for completeness. The rotor pulses, timing marks, and direction channels were scanned for normality (or what was interpreted as normal behavior). The processed 16-mm films were then ready for conversion to magnetic tape.

The film was converted on a Digital Film Recording instrument onto a reel of standard magnetic tape. The tape was recorded at 200 characters per inch into an IBM 7 channel binary format. Each 50-second record was read by a flying spot scanner at less than 1-second intervals. The format for reading on magnetic tape varied according to the film reading agency used. One such format was as follows:

Format for Film Reading

a. 120-character Hollerith identification including lake name and speed units.

b. 120 characters of numeric information

1	15	Film number (5 digits, one zero omitted)	5
	4X		
2	13	Station Number	12
	3X		
3	13	Depth (meters)	18
	3X		
4	12	Time between observations 20 or 30	23
	3X		
5	14	Starting foot mark	30
6	12	+Sprocket holes	33
	2X		
7	12	Month 01 - 12	37
8	12	Day 01 - 31	39
9	12	Year (last 2 digits)	41
10	12	Hours	43
11	12	Minutes	45
	3X		
12	14	Ending foot mark	52
	1X		
13	12	+Sprocket holes	55
	2X		
14	12	Month	59
15	12	Day	61
16	12	Year (last 2 digits)	63
17	12	Hours	65
18	12	Minutes	67
	1X		
19	14	Number of read pulses	72
	1X		

Tape Data Format

11	type	
13	compass	
		12 such readings
13	vane	
13	speed	

Current meter speed was recorded in cm/sec. Current direction was defined on strip charts and computed magnetic tapes as the direction toward which the current was flowing.

Wind speed was recorded in miles per hour. Wind direction was defined on computed magnetic tapes as the direction toward which the wind was blowing. In processing data 180° was added to computed direction to present data in the standard manner, i.e., direction from which the wind was coming.

A series of records, with identifying headings, were then sent for computer processing.

CHAPTER 5

CURRENT METER FILM PROCESSING

Specifications

The films for both the current and wind meters are read by a film reading agency using a special film scanner in connection with a computer. Both the compass and vane are read and reported in the original Gray Binary Code. Readings of the vane and compass are taken, the number of readings varying with the company.

Rotor speeds are read and interpreted by the computer. If a reading is to be meaningful, at least two rotor pulses have to be interpreted by the film reader. The instrument has two speed channels, R-1 for every rotor rotation and a R-10 for every 10 rotations. At times the R-1 rotor is jammed because the signals are too rapid and cannot be separated in the interval. This is then interpreted by the film reader as a single pulse since the light merely goes off-on-off.

The R-10 rotor is interpreted initially. If it is meaningful it is reported on magnetic tape. If it is not, then the R-1 rotor is interpreted. If meaningful information is available from the R-1, it is reported as a rotor speed; otherwise, it is reported as too slow or too fast to be read. If the read pulse cannot be found at all, this is reported, and in this case physical time is kept track of by using the film sprocket holes as a guide.

The meter information is noted on magnetic tape in the following specification format which has been adopted by the Project, the computer processor, and the film reading agencies. One method is as follows:

Each record consists of 1,080 characters.

The first record is the identification record. The first 60 characters are in IBM tape BCD code (20 = blank). These characters are supplied by the reading company. They include the lake name, speed unit, and date processed. The first character has a one as the first bit. The next 60 characters are 20 18-bit binary integers. The first 19 are supplied by the computer processor. The 20th is supplied by the reading company as the constant needed to change the speeds into proper units (miles/hr for wind records, or cm/sec for current records).

Succeeding records are broken up into words of 36 bits. Each word consists of:

4-7-7-2-7-9 bits respectively:

4 - diagnostic information

7 - vane 1

7 - compass

2 - type of data word

  0: readable data word

  1: no speed

  2: nonreadable data

  3: end of film

Note: If the word type is unity, the indicated speed will be given as 0 or 511 (the upper speed limit), depending on whether it cannot be read because it is too low or too high, respectively.

Film is started and ended as specified in the identification record. An end-of-file mark separates each film.

Each magnetic tape is checked by the computer. The printout includes the identification record, the total number of read pulses, and the first three and last three observations in each film.

Bit 1 (highest order) of the diagnostic word (first 4 bits) is zero or one, depending upon whether the speed is computed from the R-1 or R-10 rotor, respectively. The R-10 rotor speed should be multiplied by 2. This allows better resolutions for speeds.

The identification sequence as supplied by the computer service consists of the following 19 numbers:

1) Film number (second digit denotes lake -- 20 = Lake Michigan, 21 = Lake Erie, 22 = Lake Ontario, 23 = Lake Huron, 24 = Lake Superior). All film codes are in the 200,000 series.

2) Station number -- corresponds to physical location in lake.

3) Depth in meters. A zero depth is not a current meter record but is a wind recorder.

4) Time in minutes between observations -- either 20 or 30 minutes.

5) Footmark of starting point. (Footmarks are marks on original film at intervals of 1 foot.)

6) Film sprocket holes.

7) Month -- an integer, 1-12.

8) Day -- an integer, 1-31.

9) Year -- last two digits of the year

10) Hours -- based on 2400 hours.

11) Minutes -- an integer, 0-60.

Starting time for meaningful data.

12) Footmark of ending point.

13) Film sprocket holes.

14) Month.

15) Day.

16) Year.

17) Hours.

18) Minutes.

Ending time for meaningful data.

19) Total number of read pulses (time slices).

Initial Processing

A copy of the field record sheet giving the salient film identifications such as station number, starting time, ending time, depth, time between observations, etc., is sent from the Project to computer processor and to the film reading agency. After film processing, the reading agency inspects the original film and determines the starting and ending points of good data since there may be a lag of several hours between the time the instrument is set in place and the time it starts functioning properly. The starting time is reported as a combination of footmarks (which are numbered on the film at each foot) and film sprocket holes.

The 19 elements of the identification vector are punched on paper tape for input to the film scanner.

A simple consistency check is now performed on these identifications. The total number of recordings is:

a) given from inspection;

b) computable time from the given starting and ending date;

c) computable from the starting and ending footmark and film sprocket holes.

Any discrepancy among these numbers is investigated and inconsistencies are reconciled. At this point the corrected paper tape is sent on to film scanne .

The magnetic tape output is sent by the reading company to the computer processor. It is then copied on a master tape by a special control data 924 "MUPDATE" program.

The data input tape is composed of an arbitrary number of films followed by a double end of file. Each file contains an arbitrary number of records in low density. Each record contains 1,080 characters of odd parity. The first 120 characters of the first record of each file contain the file identification (i.e., 1X, 9A6, A5, 20R3). The first character is to be skipped. The second character to the 60th inclusive is in binary coded decimal (still in odd parity). Each of the next 20, three-character symbols, is to be interpreted as an 18-bit binary integer.

The output tape is a master tape which contains an arbitrary number of records of previous type (except that density is now high, 500 PSI) followed by a double end of file. Column one of the data card is zero or one, depending on whether or not the master tape is blank. The remaining columns are a job label.

Required processing: If the output tape is not blank, files are skipped until a double end of file is reached. A count of the number of files is found and noted. When new film is copied onto the master tape the second end of file is eliminated by being written over.

As each file is copied, the ordinal number of the file is printed followed by the first 120 characters of the first record in required format, and the number of records in that file. A double end of file is written at the end of processing. The copying program thus allows the handling of a single master tape instead of its many component tapes. Furthermore, it allows a measure of insurance. In case of tape failure, there remains the facility to write another master tape.

The computer is now ready for the processing of the master tape. This data processing consists of three passes. Each pass (except the first) has as its input the output tape of the preceding pass.

First Pass Program

The first pass program consists of the formation of a compact binary input tape which the computer can read quickly and efficiently. This makes it unnecessary to decode the special input formats more than once.

This initial tape generation program is buffered, i.e., while the computer is reading in one record, a previous one is being processed into its individual components (compass, vanes, speed, etc.). Vane readings are averaged into a single vane. By average, we do not mean arithmetic average, since this mean at times yields poor results (i.e., the arithmetic average of 0° and 360° is 180°). A short algorithm insures that vane readings are less than 180° apart, by judiciously adding 360° to the smaller where necessary. Only then are the angles averaged and reduced by 360° where necessary.

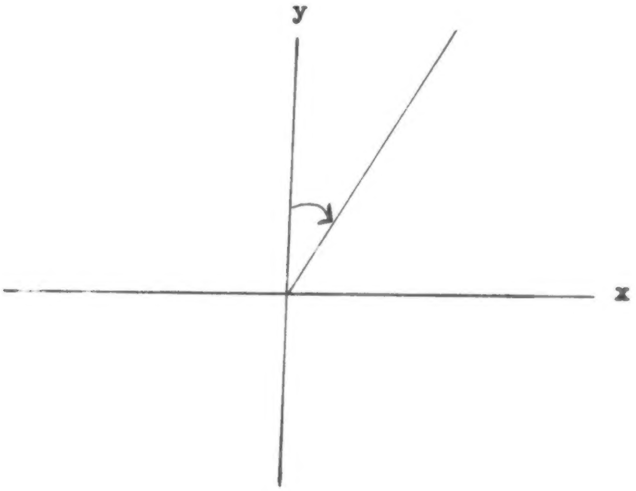


Figure 5-1

Both the compass and vane are given as a clockwise deflection from the vertical (Figure 5-1), the convention used for the vertical y axis as the major axis, and the horizontal x axis as the minor axis. The angles, although clockwise, are still to be considered positive angles, since they are formed from the major axis to the minor axis, Figure 5-2. In fact, if the above diagram were rotated 90°, its mirror image would take on the more familiar form. The basis direction is defined to be compass + vane + 180° reduced by 360° (or 720°) if necessary, so that the resulting angle is between zero and 360°. Thus, the direction is given in its meteorological mode, i.e., the direction from which the wind (or current) is coming. The speed is modified so that it is in units of miles/hr for wind recorders and cm/sec for current meters. If the speed is below the instrument range of 0.8 cm/sec it is recorded as zero. If above the instrument range, over 100 cm/sec, it is recorded as -2. If the compass and vane cannot be read (because a read pulse is missing), the speed cannot be read either. In this case both speed and angle are recorded as -1.

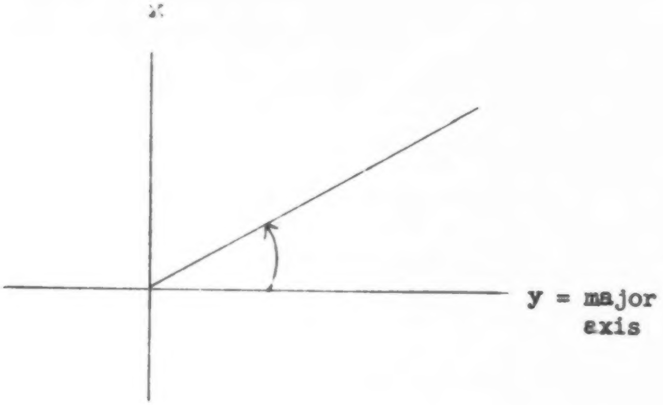


Figure 5-2

The speed and angle for every time slice are preserved on binary tape. In addition, the complete identification, the total number of read pulses (time slices) and the maximum speed actually attained are retained. This maximum speed is needed for future graphing routines so that the scales can be immediately determined. The total number of read pulses tells how to read the remainder of the data.

The original magnetic tape should have on it the correct vector identification arising from the paper tape prepared at New York University. However, under the exigencies of production processing, communications at times break down. At times the paper tapes are either incomplete or totally missing. In view of the anomalous situation, the first pass program has been modified to accept the identification sequence from cards to override the false identification on tape. The calculated risk in this procedure is readily acknowledged. A single card out of order can spoil an entire tape and void all future processing based on it. To insure against this eventuality, a special reading program has been written to scan the binary tape and print out all identifications.

Second Pass Programs

Second pass programs use the previously formed binary tape as input. At present five such programs are being run.

1) Six-hour averages

2) Histograms

3) Envelopes

4) Spectral programs

5) Filters

Six-hour averages: Six-hour averages are computed at 0, 6, 12, and 18 hours. These times were selected so that comparison could be made with official weather maps. Four parameters centered around the midpoint of each 6-hour interval are computed. These are:

1) The number of meaningful data points in the 6-hour interval. This may be zero.

2) Speed average.

3) Angle average. While speeds may be averaged, it is obviously impossible to average angles. Therefore, both speeds and angles are defined by means of horizontal and vertical components and each set of components is averaged. The average speed and angle are defined to be the vector resultant of their respective average x and y components.

4) Standard deviation of speeds in order to show a measure of dispersion.

Two days of data including station depth and date are punched on cards as a permanent record. Thus on one card we have data for eight different time slices. Each slice contains four observations. Since a card is limited to 80 columns, we are limited to two columns per observation. Both the total number of observations and the speeds obey this limitation. The angle is given to the nearest 10° so that the three-digit number can be fitted in. Thus an angle of 24 signifies an angle between 235° and 245°.

The standard deviation of speeds is more troublesome since it cannot be reduced to two digits. However, it can be shown that in most cases the standard deviation is less than the mean. Hence the standard deviation is normalized by dividing it by the mean speed. This number, which is unitless, is called the coefficient of variation. The printed value is 100 multiplied by this coefficient of variation. The resulting integer is not permitted to become greater than 99 to insure against possible (though unlikely) overflow. In symbols, the number printed is the minimum of

$$99, \ \frac{\text{100 x standard deviation of speed}}{\text{average speed}}$$

This unitless number describes the dispersion: the smaller the integer, the smaller the dispersion. Standard deviations can be readily noted by multiplying the given number by the average speed.

The resulting data are punched on cards and printed. Sample output is shown in Table 5-1.

Histograms: Two-dimensional distribution of speed versus angle is given for each month of data. The distribution of all data of a stated station at a stated depth for all months is also given. Each such distribution is given by 36 angles (each of 10°) and of 18 speeds (for current meters 3 cm/sec; for wind recorders 5 miles/hr). Total flow is given for each angle and also by total flow which is defined as $\sum S_i N_i$, where S_i is the speed in the i column (of a given row) and N_i is the number of observations there.

The marginal distributions of both speeds and angles are computed and printed. Each of these, of course, sums up the total number of observations. Note that the number may be smaller than the total number of time slices, as observations may be missing at some of these times. A sample output is given in Table 5-2.

Envelopes: A visual display of the variations of both speeds and angles in a 2-hour period was desired. A sample result is given in

TABLE 5-1

FORMAT SIX-HOUR AVERAGES

SIX HOURLY AVERAGES-STA. 13 - DEPTH 10 - TIME INTERVAL 20 MIN.

				0				6				12				18
DATE	N	D	AN	SP	N	D	AN	SP	N	D	AN	SP	N	D	AN	SP
4/11/64	18	11	1	11	18	18	2	10	18	25	5	9	18	24	8	15
	18	31	10	17	18	48	35	17	18	31	5	18	17	10	5	13
4/13/64	18	25	33	12	18	24	33	16	18	31	1	10	18	13	36	7
	18	27	0	6	18	23	36	8	18	13	0	8	18	15	36	13
4/15/64	18	13	0	14	17	25	1	11	18	18	3	6	18	10	2	12
	18	12	4	13	18	11	4	13	18	8	6	13	18	26	4	18
4/17/64	17	44	6	17	16	41	4	15	18	25	4	17	17	14	5	14
	18	13	5	13	18	15	4	11	18	23	4	7	18	31	2	4
4/19/64	13	28	2	4	17	28	35	3	13	41	35	5	15	47	2	6
	16	36	34	15	17	18	32	13	18	12	30	12	18	16	32	12
4/21/64	18	14	35	14	16	26	35	10	18	18	2	6	18	15	3	6
	18	18	6	7	18	25	7	6	17	31	9	7	16	25	9	9
4/23/64	18	19	10	10	18	19	10	8	18	14	11	9	18	18	10	8
	15	26	9	6	15	80	5	4	12	42	4	4	16	99	6	6
4/25/64	6	74	4	5	12	59	32	6	10	28	32	3	15	41	35	5
	18	16	36	9	18	35	3	6	15	24	3	3	14	27	35	4
4/27/64	18	15	36	6	15	28	4	5	16	33	4	3	16	22	5	3
	3	16	6	2	5	99	7	5	6	27	9	2	5	97	2	5
4/29/64	2	75	5	9	5	74	7	8	10	44	6	3	11	86	2	4
	8	99	29	6	8	53	32	3	5	67	31	8	7	64	5	5
5/1/64	12	46	27	5	8	95	1	5	5	73	7	8	11	26	10	3
	12	51	7	3	8	26	7	2	9	57	7	4	2	21	4	2
5/3/64	9	65	2	4	17	27	4	3	11	63	8	4	1	0	9	3
	9	66	36	5	6	46	4	8	7	21	26	4	18	32	28	7
5/5/64	18	36	29	5	17	21	31	12	18	18	31	13	18	25	31	9
	18	38	33	6	5	52	4	8	13	54	32	6	18	21	32	11
5/7/64	17	33	33	7	8	71	34	6	18	36	33	14	17	33	3	18
	18	48	3	14	18	17	3	14	18	38	1	11	18	23	2	5
5/9/64	17	36	1	4	18	20	2	5	18	25	2	4	18	11	2	5
	18	18	4	5	17	14	4	4	18	20	3	5	18	22	3	5
5/11/64	18	15	3	4	18	8	4	4	18	20	4	3	18	49	5	9
	18	23	6	15	18	21	5	16	18	15	4	14	17	12	2	14
5/13/64	18	16	7	11	18	23	7	7	18	56	7	5	7	84	32	8
	4	46	32	5	9	97	32	4	5	26	32	2	17	28	33	4
5/15/64	17	31	29	6	17	21	33	5	11	30	2	4	10	57	32	5
	18	9	36	5	10	20	4	3	5	50	34	3	15	17	3	3
5/17/64	15	29	9	3	4	42	30	11	5	94	1	5	8	83	2	6
	18	31	4	5	18	32	7	3	18	63	7	11	18	24	8	15
5/19/64	18	13	13	12	18	13	5	11	18	25	6	8	17	22	36	5
	18	15	0	5	4	34	0	3	13	29	33	4	18	14	36	5
5/21/64	18	20	0	5	18	7	0	5	18	17	1	6	18	20	3	4
	18	16	4	5	15	72	5	5	18	25	0	7	17	23	3	7
5/23/64	18	19	2	6	18	27	36	9	18	22	5	8	9	95	13	8
	16	46	32	4	16	31	2	4	4	41	16	8	17	38	29	4

TABLE 5-2

SAMPLE FORMAT OF HISTOGRAM

TWO DIMENSIONAL SPEED-ANGLE DISTRIBUTION BY MONTH IN LAKE ERIE

STATION 5. DEPTH 10. TIME INTERVAL 20. AUG. 1964

SPEED →			1	2	3	4	5	6	7	8	9		
ANGLE			1.5	4.5	7.5	10.5	13.5	16.5	19.5	22.5	25.5	TOTAL	FLOW
-5	1	5	1	4	2	10	0	0	0	0	0	17	139.5
5	2	15	8	3	7	6	3	0	0	0	0	27	181.5
15	3	25	3	22	10	13	3	0	0	0	2	53	406.5
25	4	35	4	17	4	6	8	4	0	0	0	43	349.5
35	5	45	7	21	6	18	2	0	0	0	0	54	366.0
45	6	55	9	26	43	37	12	0	0	0	0	127	1,003.
55	7	65	10	46	47	43	17	0	0	0	0	163	1,255.
65	8	75	12	36	62	50	13	1	0	0	0	174	1,362.
75	9	85	13	47	60	50	44	4	5	0	0	223	1,963.
85	10	95	25	52	50	22	22	4	0	0	0	175	1,240.
95	11	105	26	51	57	30	23	0	0	0	0	187	1,321.
105	12	115	24	42	46	28	1	3	3	2	0	149	1,030.
115	13	125	15	25	27	21	12	2	3	0	0	105	811.5
125	14	135	16	21	12	31	21	7	3	0	0	111	991.5
135	15	145	9	24	15	14	16	4	0	0	0	82	663.0
145	16	155	7	18	7	13	7	1	0	0	0	53	391.5
155	17	165	6	19	14	6	5	0	0	0	0	50	330.0
165	18	175	4	3	6	10	8	1	0	2	0	34	339.0
175	19	185	6	3	0	3	0	0	0	0	0	12	54.0
185	20	195	1	3	1	2	0	0	0	0	0	7	43.5
195	21	205	0	5	1	5	0	0	0	0	0	11	82.5
205	22	215	7	8	2	2	3	0	0	0	0	22	123.0
215	23	225	5	1	3	8	2	0	0	0	0	19	145.5
225	24	235	2	3	3	3	0	0	0	0	0	11	70.5
235	25	245	2	3	6	5	2	1	0	0	0	19	157.5
245	26	255	2	7	1	3	0	0	0	0	0	13	73.5
255	27	265	1	3	1	1	0	0	0	0	0	6	33.0
265	28	275	3	3	0	2	2	0	0	0	0	10	56.0
275	29	285	11	9	6	3	2	0	0	0	0	31	160.5
285	30	295	5	2	3	2	1	0	0	0	0	13	73.5
295	31	305	17	10	3	3	3	0	0	0	0	36	165.0
305	32	315	9	8	6	7	0	0	0	0	0	30	168.0
315	33	325	10	10	5	0	1	0	1	0	0	27	130.5
325	34	335	7	6	3	2	3	0	0	0	0	21	121.5
335	35	345	6	6	2	3	0	0	0	0	0	17	82.5
345	36	355	2	6	2	5	1	0	0	0	0	16	111.0

Figure 5-3. Note that the number in the extreme left is the ordinal day of the year representing the data. The speed scale can be formed immediately as the maximum speed is known. Instrument failure was indicated by a random array of speeds.

Both the maximum and the minimum angle and speed in a 2-hour interval were graphed side by side. If no real data points existed in the 2-hour interval, no points were graphed.

At times a series of rotations showed up with an inertial period of about 17 hours, very close to the local inertial period which varies with latitude and is 16.96 hours at 45°N.

Spectral Analysis

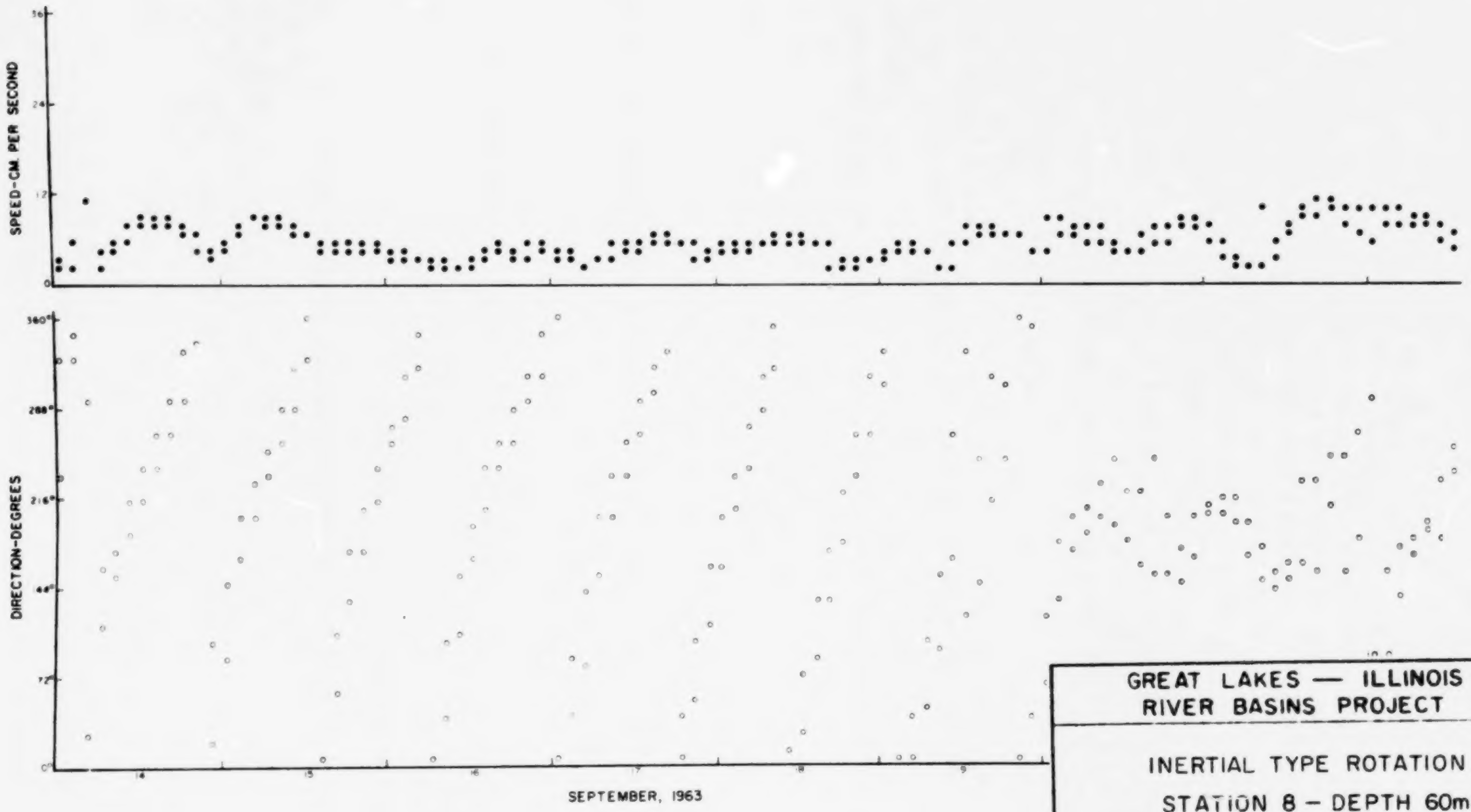
Spectral analysis is a technique for investigating the variance of a time series. It permits finding the individual components of the variance. Any marked peak in the spectrum graph is interpreted as a vital frequency. The total area under the graph is exactly equal to the variance. Thus, spectral analysis, unlike harmonic analysis, allows one to determine the sizes of the important frequencies without preknowledge of their locations.

The key number in spectral computations is an integer called the lag. The greater the lag, the more resolution one gets in studying the spectrum. The Nyquist Frequency is defined as $1/2\Delta T$ where ΔT is the time between observations. The last element of the spectrum always corresponds to this Nyquist Frequency. A lag of M will break up this basic frequency into M parts.

Thus to determine long periods, i.e., small frequencies, we need large lags. Often this is impractical because the shortness of the series does not allow long lags to be used; and, as a rule of thumb, there is nothing to be gained by using lags much longer than one-tenth of the length of the series.

One way around this difficulty is to filter the series with a low-pass filter (with consequent loss of high frequencies, although this is usually not serious) and then to decrease the Nyquist Frequency by taking, say, every fifth data point. A smaller lag, therefore, can be used to give information on the required low frequencies, as illustrated by the following example.

The current meter and wind recorder record every 20 or 30 minutes. The Nyquist Frequencies for these two sampling intervals are respectively, 1.5 and 1.0 cycles per hour (cph). If we apply a digital filter to the data which does not pass frequencies above 0.25 cycle per



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

INERTIAL TYPE ROTATION
STATION 8 — DEPTH 60m

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 5-3

hour, then 0.25 cph is an "effective" Nyquist Frequency. This means that we can subsample the 30-minute records every 4th data point (every 2hr) and subsample the 20-minute records every 6th data point (every 2hr). Subsampling every 2 hours yields a Nyquist Frequency of 0.25 cph. Thus, the number of filtered data points which we must lag with each other has been reduced four- or sixfold. Since the frequency resolution of a spectral analysis is given by f_N/m (where m = number of lags), it can be seen that, if a specific resolution is desired, the effect of reducing f_N is to enable one to reduce m also. Thus, filtering and subsampling the records, has enabled us to obtain good spectral resolution in the frequency range 0.0 - 0.25 cph using fewer lags and data points than if we had not performed these operations.

Formulas

Suppose the series is x(t) for t = 1, N and M is the maximum lag. The following sequence of operations computes the power spectrum S(i) for i = 1 to M.

a) The mean of the series is removed, i.e., x(t) is replaced by

$$x(t) - \sum_{i=1}^{N} \frac{x(t)}{N}$$

where

b) The correlation function Q(i) is computed for i = 0 to M,

$$Q(i) - \sum_{t=1}^{N-1} x(t) \cdot x(t+i) \Big/ (N-i)$$

Q(0) is the variance of the series.

c) Let F(i) be the Fourier cosine of Q(i) for i = 0 ... M, i.e.,

$$F(i) = \frac{2}{M} \sum_{P=0}^{M} Q(P) \cdot \cos \frac{\pi P i}{M}$$

where Q(0) and Q(M) are replaced by half their values.

d) The spectrum function is finally computed by smoothing the above cosine transform by the 3-point Hamming formula:

$$S(i) = .25\, F_{i+1} + .5\, F_i + .25\, F_{i-1}$$

where

$$F_0 = F_2 \text{ and } F_{M+1} = F_{M-1}$$

are defined to give meaning to S(0) and s(M+1).

e) The frequency in cycles per unit time is computed in terms of the lag number as follows:

$$FRE(i) = \frac{i}{2M \cdot delt}$$

for $i = 0$ to M where delt is the time between observations. If the time is measured in hours, the frequency will be given in units of cycles/hour, etc. The period is the reciprocal of frequency.

The power spectrum at a particular frequency is the amount of power or variance in the frequency band centered around the frequency in question. The width of this frequency is given by

$$\frac{1}{2M\ delt}$$

Cross Spectrum

A cross spectrum is a generalization of spectrum analysis as applied to two series. It is actually made up of two numbers for every frequency. One is called the co-spectrum while the other is the quadrature spectrum.

If the cross spectrum of a series with itself is taken, the co-spectrum turns out to be the spectrum of the series while the quadrature spectrum is identically zero.

The formulas are quite analogous. Again we remove the average from both sides. We then lag both series separately.

$$P(i) = \frac{\sum x(t)\ y(t+i)}{N-i}$$

$$Q(t) = \frac{\sum x(t+i)\ y(t)}{N-i}$$

We now define the correlation function to be half the sum and half the difference of P and Q, i.e.,

$$Q_1(i) = \frac{P(i) + Q(i)}{2}$$

$$Q_2(i) = \frac{P(i) - Q(i)}{2}$$

We now find the Fourier cosine transform of Q_1 and the Fourier sine transform of Q_2. (The formula for the latter is identical with that of cosine transform of replacing cosine with sine.) After respective three-point smoothings as before, the resulting functions are defined as the co-spectrum (C_o) and quadrature (quad).

Coherence, $C_{(i)}$, is the measure of the relation between both series at a particular frequency.

$$C_{(i)} = \sqrt{\frac{C_o^2(i) + \text{quad}^2(i)}{SP1(i)\ SP2(i)}}$$

where SP1(i) and SP2(i) are the respective spectra of the individual series. It can be shown that coherence must be a number between zero and one. A coherence close to zero shows very little correlation between series. A coherence close to one means that series are highly correlated at that frequency.

Graphing

Digital graphs are especially useful. For their description, see Mehr (51).

An analog plotter was extensively used to replace the digital envelope.

The resulting graph is both more accurate and esthetically satisfying. However, its usefulness is marred by the long lag time between the digital program and its resulting graph for long runs.

Third Pass Programs

Third pass programs employ 6-hour average cards as input.

Trajectory programs: The 6-hour speed and angle data were used to plot the path of a mythical point being moved at these average speeds. Two days of data were given a single diagram. Two diagrams made up a page. The starting point was at the center of the diagram. Succeeding points were designated by succeeding letters of the alphabet. If a letter was missing, it had obviously been written over by a succeeding letter. (See Figure 5-4.) Major trends over a period of several days were thus readily observable.

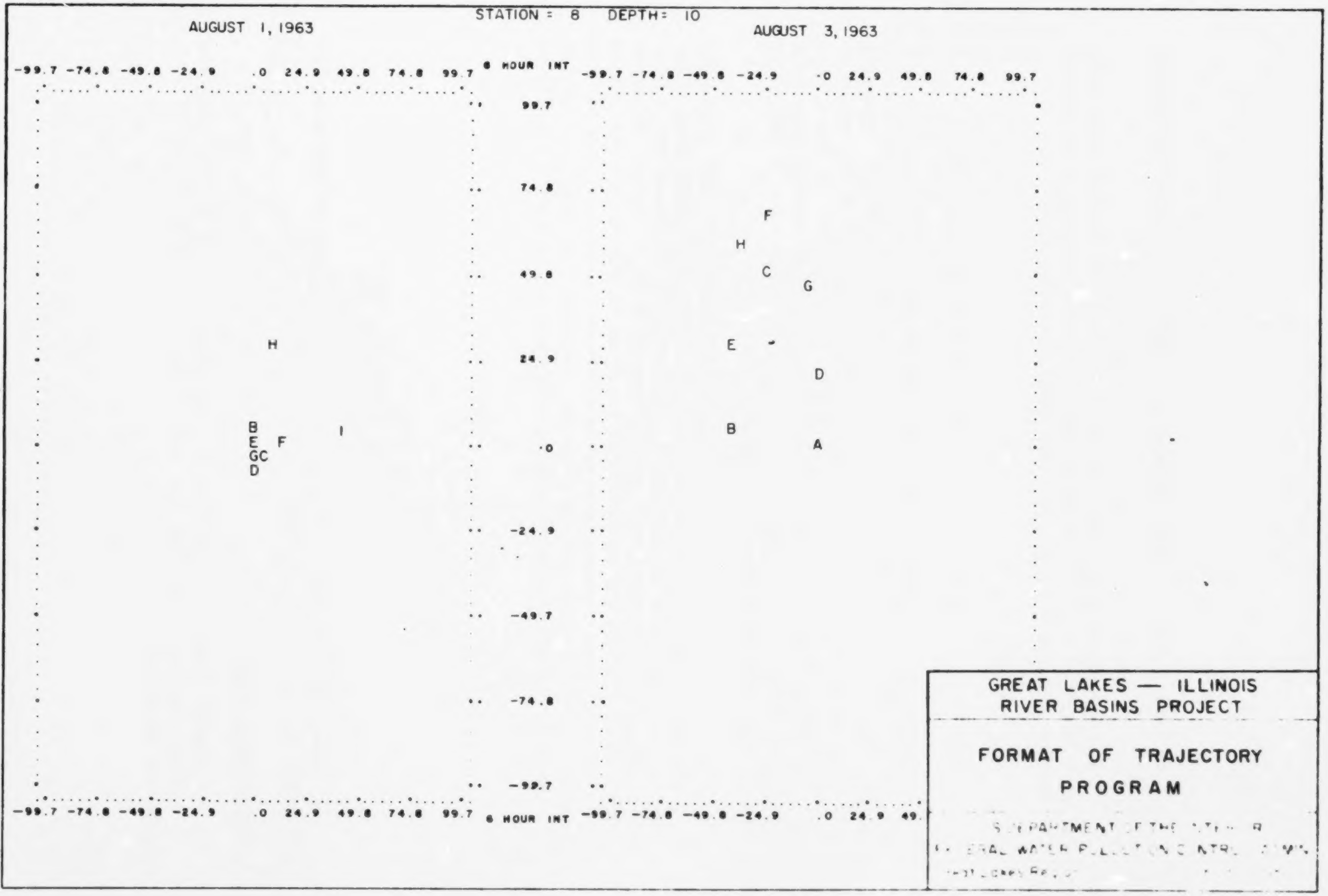
Maps: To study the 6-hour data intelligently, it was necessary to study data from all stations at a given depth at a given time. The computer printed out a map of Lake Michigan for every 6-hour period for every depth having data in a key 3-month period (October-December 1963). Each station was marked by an asterisk in its correct geographical position. Dots represented the boundary of the Lake. If data were present at a particular station, the four parameters described above (for 6-hour averages) were printed as four integers around the station.

```
10    15

   *

2     7
```

These maps allowed us to assimilate many terms of data simultaneously, as illustrated by Figure 5-5.

Temperature Data

Hourly temperature data have been obtained from various stations at several depths. Computations are used to determine the basic frequencies by means of:

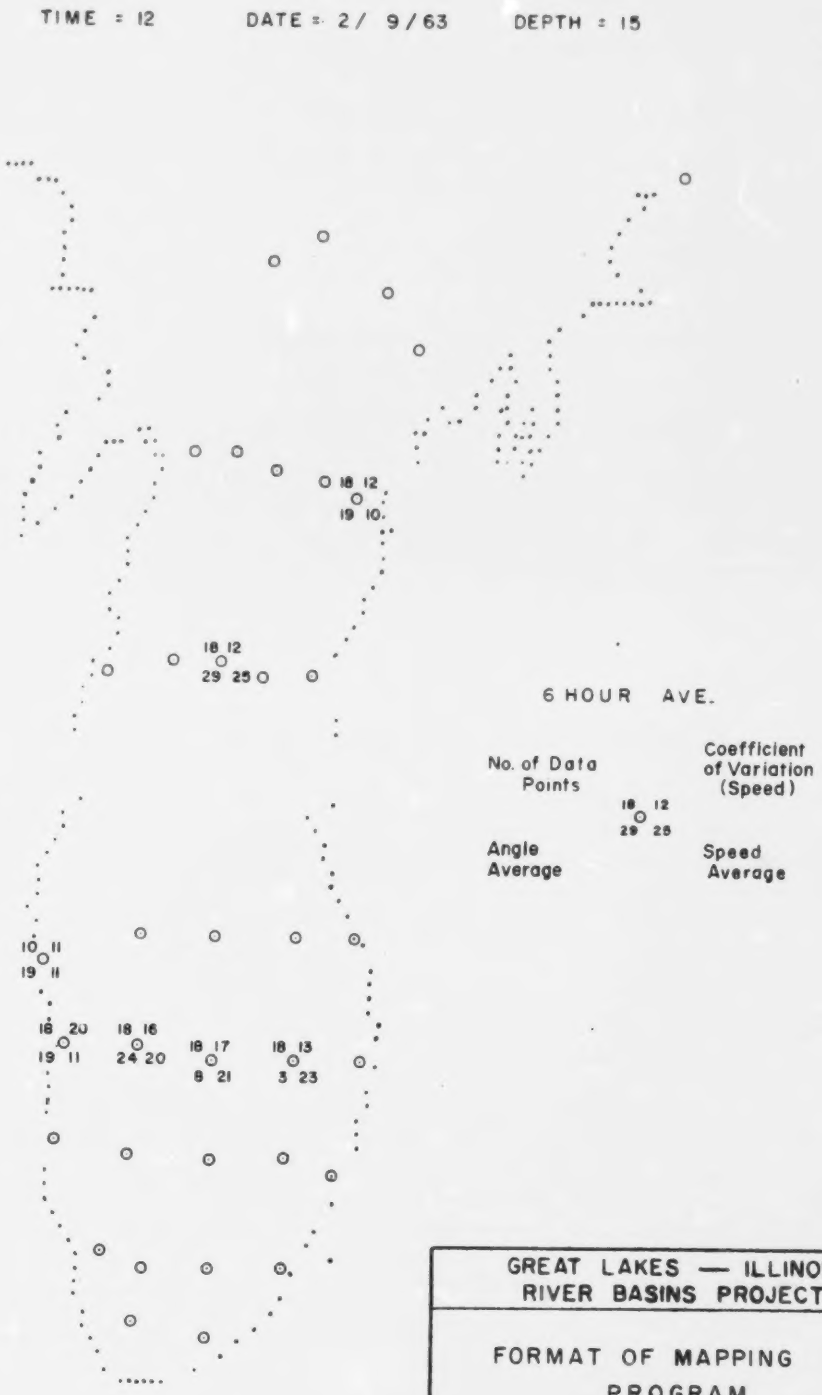


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

FORMAT OF TRAJECTORY
PROGRAM

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region [illegible]

FIGURE 5-4


TIME = 12
DATE = 2/ 9/63
DEPTH = 15
18 12
19 10
18 12
29 25
6 HOUR AVE.
No. of Data Points
Coefficient of Variation (Speed)
18 12
29 25
Angle Average
Speed Average
10 11
19 11
18 20
19 11
18 16
24 20
18 17
8 21
18 13
3 23

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

FORMAT OF MAPPING
PROGRAM

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 5-5

a) Spectral analysis.

b) Harmonic analysis.

It is known that any finite sequence can be written as a finite Fourier Series. It is too costly to compute all frequencies. However, a band of five harmonics was taken around every suspected major frequency. Furthermore, the powers at these frequencies were computed so that the percentage of the variance of the original series, that was accounted for at each of these frequencies, could be found. Finally, the percentage of the variance that was unaccounted for by any of the frequencies was noted.

c) Regression analysis.

A linear least squares model was computed based on particular suspected frequencies. The standard error and the coefficient of correlation were also computed. The former is the square root of the average of the square of the deviations, while the latter is a measure of the percentage of the variance that is accounted for by this particular model.

Drogue Surveys

Drogue surveys of lake currents near Chicago were undertaken by the GLIRB Project. The mechanical details are reported in Chapter 8. The original data consisted of aerial photographs on color film. Every drogue was identified by shape and color. Dr. Akira Okubo of Johns Hopkins University proposed a series of computations on the data matrix consisting of the x-y positions of each of the drogues at each of the time slices. These computations consisted of the calculation of means and standard deviations of x values and y values, in both time and space. For each time slice, the center of gravity of the drogues was found. The collection of distances between any two points was studied. Histograms were formed, and moments computed. The results of these computations and their interpretation have been reported by Dr. Okubo.

Most of the effort expended was comprised of obtaining the data needed for the Okubo computations from the aerial photographs. Essentially the problem consisted of finding local coordinates for every time slice, i.e., a common coordinate system had to be constructed for all frames of a particular time slice. Global coordinates for every time slice also had to be found, i.e., a common coordinate system had to be constructed for all time slices.

It was assumed that the plane was flying level as the photographs were taken. This implied that the equations of transformation from the UV local plane to the xy global plane was:

$$x = A(1)U + A(2)V + A(3)$$

$$y = A(2)U - A(1)(V) + A(4)$$

where $A(1) = \rho \cos \theta$, $(2) = \rho \sin \theta$ in terms of the magnification factor, ρ, the rotation angle θ, and the translation of the origin of UV coordinate system to the point $A(3)$, $A(4)$ in the xy plane. Coordinates of the two fixed points needed to be given in both coordinate systems to determine the transformation constants, since this yielded four equations in the four unknowns $A(1)$, $A(2)$, $A(3)$, and $A(4)$.

It is believed that more accurate results would have been obtained without the assumption that the plane was level. However, we could not proceed without it, since at times only two common points were given. As a matter of fact, at times, even two fixed points could not be found which were common to two successive frames. In these cases, a slow moving drogue had to be considered as a temporary fixed point. Since this assumption was not abused, it caused no difficulty, i.e., it was used only between frames of the same time slice and not between time slices. Furthermore, if the same drogue was used as a fixed point at two separate times, it was given a different name to avoid confusion.

At times as many as five fixed points could be found common to the successive frames. In these cases the equations are over-determined. It was decided to use least squares. The following quantity was to be minimized:

$$\sum\left[\overline{A(1)U_i + A(2)V_i + A(3) - x_i}^{\,2} + \overline{A(2)U_i - A(1)V_i - y_i}^{\,2}\right]$$

Differentiating with respect to the unknowns $A(i)$ yielded the following equations:

$$\begin{pmatrix} e & 0 & b & c \\ 0 & e & c & -b \\ b & c & d & e \\ c & -b & 0 & d \end{pmatrix} \begin{pmatrix} A(1) \\ A(2) \\ A(3) \\ A(4) \end{pmatrix} = \begin{pmatrix} f \\ g \\ s_x \\ s_y \end{pmatrix}$$

where:

$$b = \sum w_i U_i$$

$$c = \sum w_i V_i$$

$$d = \sum w_i$$

$$e = \sum w_i (U_i U_i + V_i V_i)$$

$$f = \sum w_i (U_{x_i} + V_{y_i})$$

$$g = \sum w_i (U_{y_i} + V_{x_i})$$

$$s_x = \sum w_i x$$

$$s_y = \sum w_i y$$

where w represents the weight of a particular observation. Thus a real fixed point can be assigned a higher weighting factor than a temporary fixed point. Varying weights are not used in the first run.

It can easily be verified that the required solution to the matrix equation is

$$A(1) = (fd - bs_x - cs_y)/Q$$

$$A(2) = (gd - cs_x + bs_y)/Q$$

$$A(3) = (-fb - cg + es_x)/Q$$

$$A(4) = (-fc + bg + es_y)/Q$$

and where $Q = ed - b^2 c^2$

The above relations are imbedded in subroutine TRANS (NAX, U, V, X, Y, A) which determines A(i), i = 1...4 from NAX sets of xy and UV coordinates.

The first program is called COFIX, the reduction of all fixed points to a common coordinate system. At the start, we were given global coordinates of only two points. To find the third point, we were given local coordinates of the two fixed points and the third point. We now computed the transformation and transformed the third point to its global coordinates. These coordinates were punched out on cards for future use and were added to the memory bank of fixed points.

The computation of the fourth global coordinate depended on two or three (in this case) fixed points. The same subroutine was again utilized. At each stage, the fixed points were recomputed. No discrepancy could be found.

In general, the computation of the Nth fixed point depended on N-1 common fixed points to the global and the local coordinate system. (In practice, no more than six common points were found.) The output of this program was the deck of fixed points in global coordinates.

The actual data were now ready to be processed and the global coordinates of all data points in each time slice were computed as required by the Okubo program.

The first card was a time slice identification card telling the number of frames in the particular time slice and the corresponding frame identifications. A frame identification card was processed for each such frame. It consisted of:

(a) The number of drogues in the frame.

(b) The number of fixed points in the frame.

(c) Identification numbers for the fixed points of both x and y local coordinates for each such fixed point in the frame.

Since the number in (b) was assumed no greater than five, it was possible to get all the information in (a), (b), and (c) on one card in addition to a job and time slice identification in order to insure that the cards were in proper order.

The global coordinates of these fixed points (which were read into the computer memory) were now called on and the equation of transformation from the frame to the global coordinates was found. The local coordinates could now be read. The drogue data were read for the frame which had drogue identification, and its corresponding x and y coordinates. It was known from the frame identification how many drogues were expected. Then each drogue was transformed to its global coordinate. A check was made to find out if a global determination of this drogue in this particular time slice had been made previously. If so, the two determinations were averaged.

After completing the particular frame, another frame identification card was read and continued as before. Since the expected number of frames in a particular time slice was known, the end of a time slice was known. The list of all drogues was saved for reference in that time slice with their corresponding global coordinates.

The computer distinguishes between real data and missing data by denoting the latter by zero. In the printing program, missing data were denoted by x = 0 and y = o. The only point at which a human might be confused was the origin, which might conceivably be (0, 0) or, most likely, missing. However, the computer cannot be confused since care was taken to add some noise, about 10^{-25} at each meaningful point. Therefore, the computer distinguished between a real zero and a fictitious zero to denote a missing point. The fictitious zero was actually zero while the real zero was simply very close to zero.

Each succeeding time slice was now processed in a similar manner until all time slices were processed. The resulting tape was used as input for further processing of the Okubo program.

CHAPTER 6

CURRENT STUDIES

Introduction

Preceding sections of this report have described the methods, techniques, testing, and other activities connected with the study of currents on Lake Michigan. This Chapter details the results of the study.

Before the data from unattended current meters and anemometers can be published or released for further usage, the first step must be the assessment of reliability (timing, direction, and speed) of the data. Assuring correct timing is one of the most difficult problems. The clocks may run slow (or fast) by a fraction of a second in an hour and thus be inaccurate for an hour or more at the end of a 6-month record. Using techniques of 2-hour envelopes (showing the maximum and minimum readings in a 2-hour period) and 6-hour averages does not eliminate the error but such errors are insignificant over such a short period. In reporting monthly net flows and histograms, the probable error is less than 0.5 percent.

It was noted early in dealing with the 6-hour averages that the current speeds responded to a wind input. This response was found in the currents from top to bottom regardless of current direction. All speed records were analyzed to correct any obvious errors which may have arisen from automatic scanning or instrument deficiencies.

By comparing, for each instrument, the length of the records with the known times at which the instrument was set in and recovered from the Lake, it is possible to arrange the records on a quality scale as shown in Table 6-1. Over half of the records show differences between recorded time and the known time of less than 40 minutes, and the maximum error for the remaining records, when corrected, was less than 2½ hours.

TABLE 6-1
TIMING ACCURACY OF CLOCKS

QUALITY	MAXIMUM HOURLY RANGE/MONTH CORRECTED
A	0 to 1
B	1 to 2.5
C	2.5 to 5
D	5 to 10
E	Over 10

Ranges B, C, and D permit monthly evaluation but are not usable for accurate 6-hour averages unless corrected. Range E, unless corrected, is considered poor quality and normally discarded. On an average, the maximum time error permitted is limited to 1 percent. The quality of the time values is usually based on the percent error in the total record.

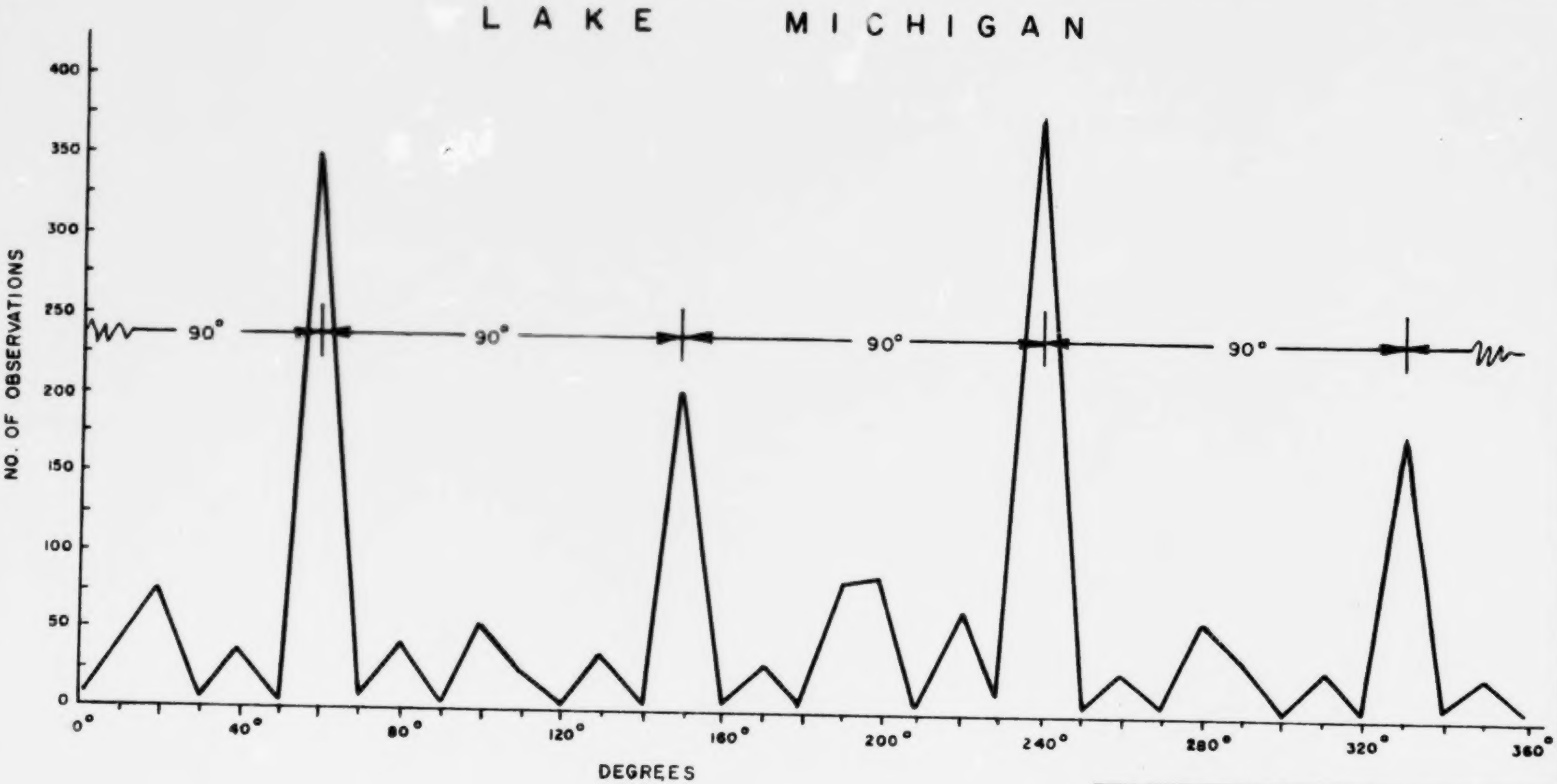
Direction errors are not difficult to detect unless the meter is off by an unknown number of degrees. The instruments are checked prior to setting and after retrieval to reduce this error to zero. Under certain circumstances the direction is meaningless, due to turbulence or other factors; and a record of this type is discarded. A certain objectivity enters into the search for errors in direction. Visual scanning of millions of data points reveals certain constantly repeated patterns. These patterns form the basis for ascertaining good versus bad data. Water movements, especially direction patterns do not repeat specific degrees over any long time period. Thus, a record which shows repetition of the same degrees for more than 4 hours is immediately suspect. Figure 6-1 shows a histogram of data which produced false modes due to blurring of the light pipes. Blurring is due to the rapid fluctuation of the vane and the light pipes appear (when scanning by electronic methods) as permanently in the "on" position. This blurring appears at certain stations and not others. All films were visually inspected to remove films which had serious blurring problems. Quality values based on the percent of blurring indicate the quality of the direction data.

Speed values are scanned similar to directions. Values below 1 centimeter per second (cm/sec) are discarded. Long-term high or low values are questioned and checked against similar stations nearby. On many occasions high values occur and appear to be due to reading problems in the automatic scanning of the records. New reading techniques have nearly eliminated these errors. Quality values, based on the percent of spurious high values, indicate the reliability of the speed data.

Data Compilation

After the data had been compiled into the several forms used for review purposes by computer printouts, the master lists for identification were prepared. Current data were identified in master lists by film number (200 000 series, see Net Flows) and by station.

The original station number in Lake Michigan included 61 stations of which 38 were actually used in the study. One station was added (number 62) near the tower erected for the U. S. Weather Bureau at Muskegon, Michigan. The locations are shown on Figure 6-2 and are identified by longitude and latitude in Table 6-2.



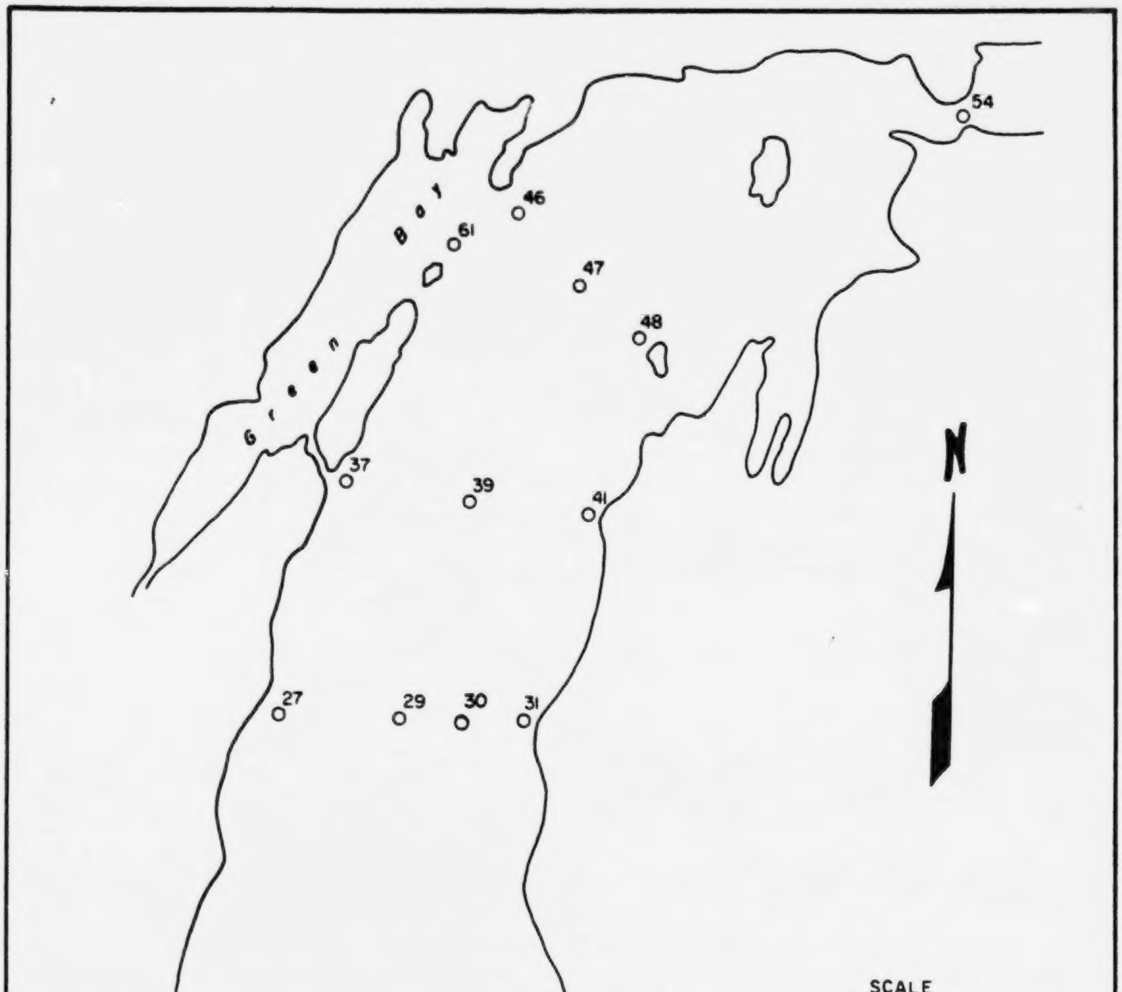
Total observations: 1959
Total in four sectors: 1115

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

HISTOGRAM OF BLURRING
STATION 47, 10METERS

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-1


54
Green Bay
46
61
47
48
N
37
39
41
27
29
30
31
SCALE
0
40 Kilometers
17
18
19
20
21
62
12
13
14
15
16
STA. 13
7
8
9
10
11
3
4
5
6
1
2

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CURRENT STATION LOCATIONS

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6 – 2

TABLE 6-2

CURRENT METER RECORDS

STATION	DEPTH (METERS)	FILM NO. 200 -	LATITUDE	LONGITUDE	TOTAL DEPTH (METERS)	DATE IN	TIME (CST)	DATE OUT	TIME (CST)	TOTAL HOURS IN WATER
001	010	033	41°48'	87°20.5'	20.1	03/31/63	1020	07/26/63	1350	2812
003	010	004	42°02.5'	87°32'	19.5	12/17/62	1530	03/22/63	1300	2280
	015	005				12/17/62	1530	03/22/63	1300	2280
004	010	000	42°01'	87°20'	46.6	12/18/62	0815	03/22/63	1550	2264
	015	001				12/18/62	0815	03/22/63	1550	2264
	022	002				12/18/62	0815	03/22/63	1550	2264
	030	044				03/28/63	1125	10/15/63	1430	4827
	022	203				11/17/63	1300	04/12/64	0916	3524
	010	347				04/12/64	0825	07/08/64	0705	2077
	030	368				04/12/64	0825	07/08/64	0705	2077
005	015	197	41°59'	87°00'	62.5	11/25/63	0900	04/12/64	1455	3342
	030	199				11/25/63	0900	04/12/64	1455	3342
	060	200				11/25/63	0900	04/12/64	1455	3342
	015	324				05/12/64	1035	07/06/64	0855	1318
007	010	120	42°25'	87°45'	22.2	07/30/63	1500	11/09/63	1708	2450
	015	121				07/30/63	1500	11/09/63	1708	2450
	010	185				11/18/63	0800	04/02/64	0900	3265
	010	321				04/10/64	1410	06/16/64	1300	1607
008	060	049	42°23'	87°25'	100.6	07/30/63	1730	10/16/63	1100	1866
	022	056				07/30/63	1730	10/16/63	1100	1866
	030	057				07/30/63	1730	10/16/63	1100	1866
	015	063				07/30/63	1730	10/16/63	1100	1866
	010	065				07/30/63	1730	10/16/63	1100	1866
	015	374				11/24/63	1000	04/10/63	1700*	3319
009	022	051	42°23'	86°59'	134.4	08/18/63	1330	10/17/63	1035	1435
	120	052				08/18/63	1330	10/17/63	1035	1435
	030	053				08/18/63	1330	10/17/63	1035	1435
	090	054				08/18/63	1330	10/17/63	1035	1435
	060	058				08/18/63	1330	10/17/63	1035	1435
	015	062				08/18/63	1330	10/17/63	1035	1435

***Estimated**

TABLE 6-2 (Continued)

CURRENT METER RECORDS

STATION	DEPTH (METERS)	FILM NO. 200 -	LATITUDE	LONGITUDE	TOTAL DEPTH (METERS)	DATE IN	TIME (CST)	DATE OUT	TIME (CST)	TOTAL HOURS IN WATER
010	015	050	42°23'	86°38'	66.1	08/16/63	1045	10/17/63	0805	1485
	022	060				08/16/63	1045	10/17/63	0805	1485
	030	061				08/16/63	1045	10/17/63	0805	1485
	060	043				08/16/63	1045	10/17/63	0805	1485
	015	230				11/25/63	1600	04/15/64	0900	3401
	022	231				11/25/63	1600	04/15/64	0900	3401
	030	232				11/25/63	1600	04/15/64	0900	3401
	060	233				11/25/63	1600	04/15/64	0900	3401
	010	316				05/11/64	1535	07/05/64	1352	1318
	015	317				05/11/64	1535	07/05/64	1352	1318
	022	318				05/11/64	1535	07/05/64	1352	1318
011	015	123	42°21'	86°21'	20.1	08/06/63	0950	11/08/63	1220	2257
012	010	124	42°46'	87°42'	22.2	07/31/63	1020	11/10/63	0730	2445
013	010	236	42°45'	87°21.8'	117.0	11/19/63	1030	04/10/64	1002	3431
	015	237				11/19/63	1030	04/10/64	1002	3431
	022	238				11/19/63	1030	04/10/64	1002	3431
	030	239				11/19/63	1030	04/10/64	1002	3431
	090	241				11/19/63	1030	04/10/64	1002	3431
	010	350				04/10/64	0915	07/08/64	1510	2142
	015	351				04/10/64	0915	07/08/64	1510	2142
	022	352				04/10/64	0915	07/08/64	1510	2142
	030	353				04/10/64	0915	07/08/64	1510	2142
	060	354				04/10/64	0915	07/08/64	1510	2142
	090	355				04/10/64	0915	07/08/64	1510	2142
014	022	126*	42°41'	86°55'	161.0	08/05/63	1530	11/07/63	1800	2018
	030	127				08/05/63	1530	11/07/63	1800	2018
	060	128				08/05/63	1530	11/07/63	1800	2018
	120	130				08/05/63	1530	11/07/63	1800	2018
	150	131				08/05/63	1530	11/07/63	1800	2018
015	022	183	42°44'	86°35'	87.8	08/05/63	1900	12/11/63	1030	3063
	010	242			89.6	11/26/63	0830	04/15/64	1200	3388
	022	244				11/26/63	0830	04/15/64	1200	3388
	060	246				11/26/63	0830	04/15/64	1200	3388

*Previously labeled 200 174.

TABLE 6-2 (Continued)

CURRENT METER RECORDS

STATION	DEPTH (METERS)	FILM NO. 200 -	LATITUDE	LONGITUDE	TOTAL DEPTH (METERS)	DATE IN	TIME (CST)	DATE OUT	TIME (CST)	TOTAL HOURS IN WATER
016	010	133	42°44'	86°15'	20.1	08/04/63	1720	11/08/63	0900	2296
017	010	008	43°08'	87°51'	21.9	12/01/62	1035	04/19/63	1100	3096
	015	180				07/16/63	1000	11/21/63	0830	3070
	015	188				11/21/63	0900	04/02/64	1515	3196
	010	356				04/02/64	1615	07/09/64	1225	2118
	015	357				04/02/64	1615	07/09/64	1225	2118
018	010	009	43°09'	87°28'	79.8	11/29/62	1550	04/20/63	0900	3401
	030	012				11/29/62	1550	04/20/63	0900	3401
	060	191	43°08'	87°24.5'		11/21/63	1300	04/09/64	1236	3360
	030	192				11/21/63	1300	04/09/64	1236	3360
020	015	015	43°08'	86°32'	104.2	11/28/63	1530	04/22/63	1345	3478
	030	017				11/28/63	1530	04/22/63	1345	3478
	090	019				11/28/63	1530	04/22/63	1345	3478
	022	137				07/12/63	1115	11/07/63	1330	2834
	060	139				07/12/63	1115	11/07/63	1330	2834
	090	140				07/12/63	1115	11/07/63	1330	2834
	010	247				12/07/63	0930	04/15/64	1830	3070
	060	251				12/07/63	0930	04/15/64	1830	3070
	010	306				05/10/64	1005	07/05/64	0745	1342
	015	307				05/10/64	1005	07/05/64	0745	1342
	022	308				05/10/64	1005	07/05/64	0745	1342
	030	309				05/10/64	1005	07/05/64	0745	1342
	090	311				05/10/64	1005	07/05/64	0745	1342
021	010	330	43°08'	86°19'	18.3	07/12/63	1230	06/02/64	1330	*
027	010	116**	44°03'	87°33'	32.3	08/21/63	1000	10/28/63	1605	1638
	022	118				08/21/63	1000	10/28/63	1605	1638
	015	212				12/04/63	0845	04/23/64	1020	3385
	010	358				04/23/64	1020	07/10/64	0600	1868
	015	359				04/23/64	1020	07/10/64	0600	1868
	022	360				04/23/64	1020	07/10/64	0600	1868
028	022	207	44°04.5'	87°14.5'	137.2	12/04/63	1144	04/23/64	1430	3386
	010	361				04/23/64	1400	07/10/64	0757	1866
	015	362				04/23/64	1400	07/10/64	0757	1866
	060	365				04/23/64	1400	07/10/64	0757	1866
	120	367				04/23/64	1400	07/10/64	0757	1866

*Station originally lost, end computed.
**Previously labeled 200 016.

TABLE 6-2 (Continued)

CURRENT METER RECORDS

STATION	DEPTH (METERS)	FILM NO. 200 -	LATITUDE	LONGITUDE	TOTAL DEPTH (METERS)	DATE IN	TIME (CST)	DATE OUT	TIME (CST)	TOTAL HOURS IN WATER
029	010	107	44°06.5'	87°00'	157.3	08/20/63	1800	10/28/63	1220	1650
	015	108				08/20/63	1800	10/28/63	1220	1650
	022	109				08/20/63	1800	10/28/63	1220	1650
	060	111				08/20/63	1800	10/28/63	1220	1650
030	015	254	44°04'	86°48'	152.4	12/05/63	0900	04/19/64	0835	3263
	030	256				12/05/63	0900	04/19/64	0835	3263
	060	257				12/05/63	0900	04/19/64	0835	3263
	090	258				12/05/63	0900	04/19/64	0835	3263
	120	259				12/05/63	0900	04/19/64	0835	3263
	150	260				12/05/63	0900	04/19/64	0835	3263
	022	300				04/19/64	0705	07/04/64	0925	1826
	030	301				04/19/64	0705	07/04/64	0925	1826
031	010	142	44°04'	86°33.3'	70.4	08/20/63	1015	11/06/63	1830	1880
	015	143				08/20/63	1015	11/06/63	1830	1880
	022	144				08/20/63	1015	11/06/63	1830	1880
	030	145				08/20/63	1015	11/06/63	1830	1880
037	030	104	44°50'	87°09'	66.4	08/23/63	0930	10/29/63	1120	1610
	010	261				12/02/63	0900	04/20/64	1717	3368
	030	264				12/02/63	0900	04/20/64	1717	3368
	022	295				04/20/64	1610	07/03/64	0740	1767.5
	030	296				04/20/64	1610	07/03/64	0740	1767.5
	060	297				04/20/64	1610	07/03/64	0740	1767.5
038	010	215	44°97.5'	86°57.5'	162.8	12/02/63	1200	05/03/64	1615	3676
	030	218				12/02/63	1200	05/03/64	1615	3676
	120	221				12/02/63	1200	05/03/64	1615	3676
	060	289				04/24/64	1210	07/03/64	1220	1680
039	090	027	44°42'	86°45'	246.9	12/02/62	1550	07/19/63	1000	5490
	150	029				12/02/62	1550	07/19/63	1000	5490
	210	031				12/02/62	1550	07/19/63	1000	5490
	240	032				12/02/62	1550	07/19/63	1000	5490
	022	150	44°45'	86°45'		08/22/63	1630	11/06/63	1045	1818
	030	151				08/22/63	1630	11/06/63	1045	1818
	120	154				08/22/63	1630	11/06/63	1045	1818
	180	156				08/22/63	1630	11/06/63	1045	1818
	150	155*				08/22/63	1630	11/06/63	1045	1818

*200 155 mislabeled 200 176.

TABLE 6-2 (Continued)

CURRENT METER RECORDS

STATION	DEPTH (METERS)	FILM NO. 200 -	LATITUDE	LONGITUDE	TOTAL DEPTH (METERS)	DATE IN	TIME (CST)	DATE OUT	TIME (CST)	TOTAL HOURS IN WATER
040	010	266	44°43'	86°31'	195.7	12/03/63	1130	04/19/64	1627	3316
	060	270				12/03/63	1130	04/19/64	1627	3316
	120	272				12/03/63	1130	04/19/64	1627	3316
041	010	160	44°39'	86°20'	188.4	08/22/63	1000	11/05/63	1430	1804.5
	015	161				08/22/63	1000	11/05/63	1430	1804.5
	090	165				08/22/63	1000	11/05/63	1430	1804.5
	120	166				08/22/63	1000	11/05/63	1430	1804.5
046	015	097	45°33'	86°34'	43.3	10/06/63	1415	10/29/63	1855	0557
	030	099				10/06/63	1415	10/29/63	1855	0557
047	010	087	45°22'	86°14'	159.1	10/04/63	1425	10/31/63	1835	0653
	015	088				10/04/63	1425	10/31/63	1835	0653
	030	090				10/04/63	1425	10/31/63	1835	0653
	060	091				10/04/63	1425	10/31/63	1835	0653
	090	092				10/04/63	1425	10/31/63	1835	0653
	150	094				10/04/63	1425	10/31/63	1835	0653
048	010	082	45°12'	86°02'	45.4	10/04/63	1115	10/31/63	2040	0658
054	010	077	45°48.5'	84°44.5'	31.4	09/24/63	1505	10/30/63	2115	0870
	022	079				09/24/63	1505	10/30/63	2115	0870
	030	080				09/24/63	1505	10/30/63	2115	0870
061	010	072	45°27'	86°47'	48.8	09/23/63	1245	10/29/63	1700	0868
	015	073				09/23/63	1245	10/29/63	1700	0868
	022	074				09/23/63	1245	10/29/63	1700	0868
062	010	171	Muskegon Tower		15.0	08/04/63*	0930	10/30/63	0800	2086.5
	015	173				08/04/63*	0930	10/30/63	0800	2086.5
	022	369				06/22/64**	0815	09/28/64	0800	2352

*Started on land 40.5 hrs earlier, time shown is in water only.
**Started on land 16 hrs earlier, time shown is in water only.

The master list for data identification by film number is shown in Table 6-3 and by station in Table 6-2. These two cross referenced lists permit rapid identification of all data from the original computer printouts. The data included in the master list have been corrected for time by methods previously described, a check against master listings, and individual film scanning.

In addition to the master listings and data printouts, a questionnaire was prepared for field use. This questionnaire is shown as Table 6-4 and was used in conjunction with a map of the Lake. The questionnaire was directed to local fishermen who had spent many years fishing in local areas of the Lake. The purpose was to obtain detailed information concerning local areas to compare with other data obtained from the current study. Several of the questionnaires were sometimes used in one interview and supplementary sheets were added as necessary to record additional information. Unfortunately, the data secured were widely scattered, especially as to time of occurrence. After a series of interviews at three different cities, the information obtained was reviewed and summarized. The data collected were inconclusive and much too general in nature to be of any importance. Accordingly, the questionnaire method was dropped. A long-term, systematic approach might produce tangible results from this type of investigation. Fishermen who have sailed a specific area for many years are extremely helpful in gathering general information about that area.

Table 6-5 includes a brief list of conversion factors for easy reference where conversions are not shown.

Net Flows

A major objective of the current study was to determine the net circulation of the Lake and relate this to wind movements for prediction purposes. Perhaps if there were direct relationships they would have been well understood many years ago.

Drogue studies in the upper 1.5 meters (5 feet) of water show that the upper layers are directly wind-driven and respond to wind shifts in about 1 hour. This would imply that the immediate surface layers will respond to reversals in wind inputs in a matter of minutes. The depth of direct wind-driven circulations will vary from place to place, especially if a thermocline exists. The depth also depends on the wind strength and duration. Direct wind control of currents under moderate wind conditions (400 to 500 cm/sec), appears to extend to 3 to 5 meters in depth. Below this level a shear zone may exist, depending on its location, movements in adjacent parts of the Lake, and the presence or absence of a thermocline.

TABLE 6-3

CURRENT METER AND WIND RECORDER RECORDS BY FILM NUMBER

FILM NO. 200-	STATION	DEPTH (M)	FILM NO. 200-	STATION	DEPTH (M)	FILM NO. 200-	STATION	DEPTH (M)
000	004	010	068	015	000	124	012	010
001	004	015	069	013	000	126	014	022
002	004	022	070	010	000	127	014	030
004	003	010	072	061	010	128	014	060
005	003	015	073	061	015	130	014	120
008	017	010	074	061	022	131	014	150
009	018	010	076	061	000	133	016	010
015	020	015	077	054	010	137	020	022
016*	027	010	079	054	022	139	020	060
019	020	090	080	054	030	140	020	090
027	039	090	081	054	000	141	020	000
029	039	150	082	048	010	142	031	010
031	039	210	086	048	000	143	031	015
032	039	240	087	047	010	144	031	022
033	001	010	088	047	015	145	031	030
037	005	000	090	047	030	150	039	022
038	001	000	091	047	060	151	039	030
043	010	060	092	047	090	154	039	120
044	004	030	094	047	150	155	039	150
049	008	060	095	047	000	156	039	180
050	010	015	097	046	015	160	041	010
051	009	022	099	046	030	161	041	015
052	009	120	100	046	000	165	041	090
053	009	030	104	037	030	166	041	120
054	009	090	106	037	000	169	041	000
056	008	022	107	029	010	170	018	000
057	008	030	108	029	015	171	062	010
058	009	060	109	029	022	173	062	015
060	010	022	111	029	060	180	017	015
061	010	030	115	029	000	183	015	022
062	009	015	116**	027	010	185	007	010
063	008	015	118	027	022	188	017	015
065	008	010	120	007	010	191	018	060
066	008	000	121	007	015	192	018	030
067	009	000	123	011	015	197	005	015

*Number 200 116

**Mislabeled 200 016

TABLE 6-3 (Continued)

CURRENT METER AND WIND RECORDER RECORDS BY FILM NUMBER

FILM NO. 200-	STATION	DEPTH (M)	FILM NO. 200-	STATION	DEPTH (M)	FILM NO. 200-	STATION	DEPTH (M)
199	005	030	289	038	060	358	027	010
200	005	060	295	037	022	359	027	015
203	004	022	296	037	030	360	027	022
207	028	022	297	037	060	361	028	010
212	027	015	300	030	022	362	028	015
215	038	010	301	030	030	365	028	060
218	038	030	306	020	010	367	028	120
221	038	120	307	020	015	368	004	030
223	017	000	308	020	022	369	062	022
224	007	000	309	020	030	374	008	015
230	010	015	311	020	090			
231	010	022	316	010	010			
232	010	030	317	010	015			
233	010	060	318	010	022			
236	013	010	321	007	010			
237	013	015	324	005	015			
238	013	022	330	021	010			
239	013	030	334	005	000			
241	013	090	337	004	000			
242	015	010	338	015	000			
244	015	022	339	017	000			
246	015	060	340	027	000			
247	020	010	341	028	000			
251	020	060	342	030	000			
254	030	015	345	040	000			
256	030	030	346	007	000			
257	030	060	347	004	010			
258	030	090	350	013	010			
259	030	120	351	013	015			
260	030	150	352	013	022			
261	037	010	353	013	030			
264	037	030	354	013	060			
266	040	010	355	013	090			
270	040	060	356	017	010			
272	040	120	357	017	015			

TABLE 6-4

QUESTIONNAIRE

Name ______________________________ Age ______________________

Address ____________________________ Telephone __________________

____

1. Type of boat used: _______________ 2. Years fished: ___________

3. Season or seasons you fish?

Spring _____ Summer _____ Fall _____ Winter _____

4. Area normally fished: __map______ 5. Miles off shore __________

6. Do you fish other areas: map______ 7. Miles off shore __________

8. Does the current in the area you normally fish, flow in one direction during: Spring _____ Summer _____ Fall _____ Winter _____

9. Can you say if a particular wind direction or directions usually occur with the currents:

Spring _______ Summer _______ Fall _______ Winter _______

10. Have any of your nets broken loose? ________ How many times? _______

Wind direction during storm: _______ Where did nets go? __________

_______ __________

_______ __________

_______ __________

TABLE 6-5

CONVERSION FACTORS

MULTIPLY	BY	TO OBTAIN
Centimeters	0.3937	Inches
Centimeters/second	0.03281	Feet/sec
Centimeters/second	0.02237	Miles/hour
Cubic feet/sec	0.02832	Cubic meters/sec
Cubic meters/sec	35.31	Cubic feet/sec
Fathoms	6	Feet
Feet	30.48	Centimeters
Feet/sec	30.48	Centimeters/sec
Feet/sec	0.6818	Miles/hour
Knots	1.15	Miles/hour
Knots	1.85	Kilometers/hour
Kilometers	0.6214	Miles
Kilometers/hour	0.9113	Feet/sec
Kilometers/hour	0.5396	Knots
Kilometers/hour	0.6214	Miles/hour
Meters	3.281	Feet
Meters/second	3.281	Feet/sec
Meters/second	2.237	Miles/hour
Miles	1.609	Kilometers
Miles/hour	44.70	Centimeters/sec
Miles/hour	1.467	Feet/sec
Miles/hour	1.609	Kilometers/hour
Miles/hour	0.8684	Knots
Square feet	0.0929	Square meters
Square meters	10.76	Square feet

The studies in the Chicago area were about 2 km (1.25 miles) from shore in 8.2 meters of water. There is no doubt that the 6-meter drogues are influenced less by winds than by bottom topography. They are also affected by shifts in currents in the upper layers. Table 6-6 illustrates the variation of flow found in the 1.5-m and 6.1-m drogues. Approximately 75 drogues were used for each run and they were allowed to drift freely for 3.5 to 5.0 hours.

TABLE 6-6

DROGUE VARIATIONS

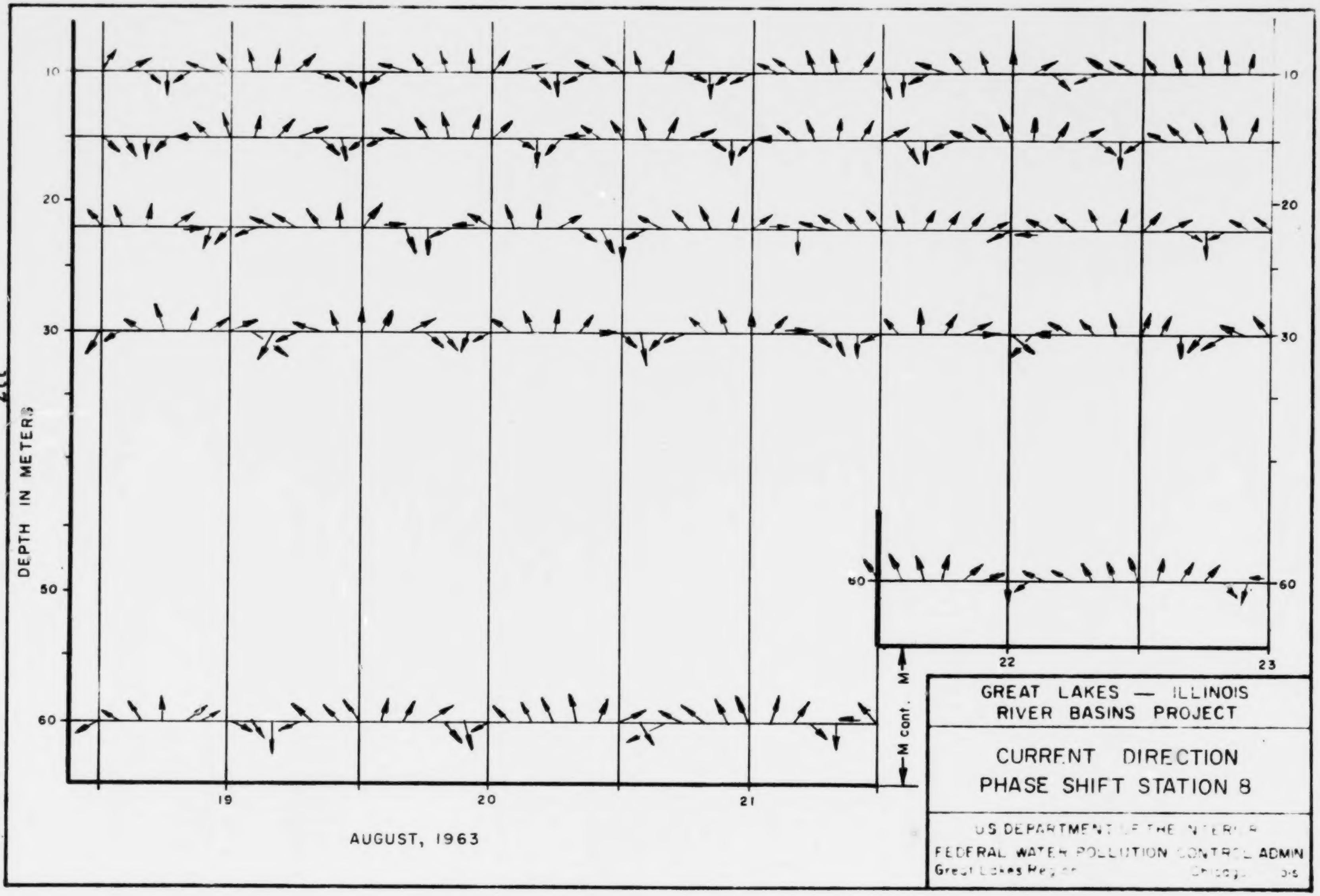
Date	Drogue Depth in Meters	Mean Wind Direction for Previous 10 Hours	Mean Wind Direction During Study	Current Direction Over Study Period
6/25/64	6.1	59°	47°	293°
6/26/64	1.5	46°	61°	84°
6/26/64	6.1	46°	61°	280°
7/15/64	1.5	80°	122°	147°
7/15/64	6.1	80°	122°	93°
8/15/64	6.1	33°	171°	102°
8/16/64	1.5	15°	94°	125°
8/16/64	6.1	15°	94°	215°

It is very apparent that the difference between the wind and currents at the 1.5-meter depth was about 27° to the right of the prevailing mean wind. However, when considered against the mean winds of the previous 10 hours, the angle is increased to 72°. The 6.1-m drogues varied greatly, both right and left of the wind, ranging from 29° to 141° during the study and from 13° to 126° for the previous 10 hours. A weak thermal discontinuity occurred between the two layers during the period of study and a shear zone existed.

When the summer thermocline had become firmly established the shear zone also existed at the interface between the epilimnion and the hypolimnion. In general, there was found to be a reversal of current direction at the thermocline such that the currents above and below this layer were moving in approximately opposite directions, i.e., approximately 180° out of phase. Such a reversal is consistent with the presence of internal waves of the first vertical mode, i.e., the internal waves which would occur in a two-layered system and which exhibit a current reversal across the boundary between the two layers. But, in Lake Michigan, the velocity does not go to zero but appears to spiral to the right in very confined layers within the upper layers of the thermocline. A zero speed level at the thermocline-epilimnion interface was not detected in any of the lakes. The so-called shear zone appears rather as a very narrow level where the currents rotated (clockwise) through 180° with increasing depth. This would account for the wind-current relationships in the thermocline (Verber, 85). Figure 6-3 at station 8 illustrates this shift. Currents are 180° out of phase, and this is confirmed by cross-spectra between velocity components of current meter data above and below the thermocline. A high coherence (0.9) was shown between the two meters at the local inertial frequency.

Internal waves of the first vertical mode, mentioned above, set in motion in a lake with relatively homogeneous upper and lower layers and a sharp thermocline, would be accompanied by an upper layer current similar in speed and direction at all depths down to just above the thermocline, a lower layer current running in the opposite direction and with little change in depth until just above the bottom. The relative speeds of the upper and lower layer currents will depend on the relative depths of the two layers, to conform with the condition that the local mass transport in each layer must be equal. This was observed by Mortimer (private correspondence and paper read at the Tenth Conference on Great Lakes Research, Toronto, April 1967, to be published) at anchor stations in July and August 1963 in mid-lake east of Milwaukee. Using current meters, with deck read-out, the vertical current structure was measured at 2-meter depth intervals down to 20 meters and at more widely spaced intervals thereafter for every 2 hours during three periods covering seven days in all. The vertical distribution of temperature was measured at the same time and a wave-like displacement of the thermocline was noted which exhibited a main periodicity of approximately 17 hours with a conspicuous component of about half that period. This internal wave increases in amplitude after a wind disturbance, and the currents, which were clearly coupled to the internal wave, also increased in speed at that time. The current direction rotated clockwise with a dominant period of 17 hours; the highest speeds observed in the upper layer were close to 40 cm/sec velocities and directions were generally similar throughout the upper layer; a reversal in direction occurred on passing through the thermocline; but the speed of the current (also rotating) in the lower layer was very much less, consistent with the greater depth of that layer.

These observations confirmed Mortimer's prediction (54) that the dominant internal wave pattern in Lake Michigan, remote from the shores and from the ends of the Lake, could be described in terms of Poincaré waves with characteristic periods close to but always significantly less than the local inertial period (17.5 hours at the latitude of Milwaukee) and with associated currents which exhibited clockwise



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

CURRENT DIRECTION
PHASE SHIFT STATION 8

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-3

rotation having the same periodicity and following an elliptical track. Mortimer showed that, just as standing waves in a closed nonrotating basin can be regarded as a combination of a progressive wave traveling in one direction with an equivalent wave of the same amplitude traveling in the opposite direction, so a pattern of standing Poincaré waves can be built up by the combinations of Sverdrup waves traveling in different directions, the Sverdrup wave being the type of long progressive wave characteristic of rotating systems in regions remote from the boundary. By contrast, near the shore where the rotating currents are ruled out by the boundary, the occurrence of Kelvin waves was predicted. In these waves, which are also a response to the Earth's rotation, the wave crests run normal to the shore and decrease exponentially in amplitude away from it, and the associated currents, which decrease in speed away from the shore, do not rotate but are constrained to run parallel to the shore. In the internal wave mode, Kelvin waves are expected to be of importance in Lake Michigan only in a near-shore strip 10 or 15 km wide. If waves of this type do, in fact, occur, the maximum currents associated with them will be close inshore and running roughly parallel to the shore but reversing in direction from time to time. Except for those waters close inshore, however, the theoretical picture suggests that the influence of internal Poincaré-type waves, expressed by rotation of the currents at near inertial frequencies, will be strongly felt elsewhere in the lake after wind disturbances. With the destruction of a thermocline in the late fall, the internal waves of both classes (Kelvin and Poincaré), of course, disappear.

The above predictions appear to be directly relevant to the Project's observations at mid-lake stations (6 km or more from the shore). During stratified conditions the short-term analysis of data does not indicate a wind-driven current system. The hour-to-hour currents are dominated by the internal wave regime which receives its principal energy from the wind. The internal wave regime is also affected by the Earth's rotation which tends to obscure the direct relationship between winds as the driving force and currents produced by internal waves. The internal wave rotation, with a period close to the inertial frequency, is often altered by sudden wind inputs. This regime lasts from late spring (April) into November or early December. The rotating influence is normally not found in the inshore waters.

By contrast, the winter circulation is less complex and almost entirely wind-driven. The major exception appears when an ice cover occurs or a reverse (winter type) thermocline develops in the central basin.

A straight prediction model, based on wind, is not valid for summer (stratified) conditions in mid-lake. Inshore current patterns in the upper 5 m appear to have a wind-driven circulation throughout the year. The response to this system appears in about 1 hour under moderate wind conditions.

The inshore zone varies in width and probably extends as much as 10 miles from the shore during the most favorable conditions and as little as 2 miles during periods of upwelling. Mid-lake circulation patterns in winter are not under the influence of internal waves except under very special conditions. Spectral analysis of current meter data, for the winter period, gives no evidence of a dominant frequency which could control current patterns. Winter patterns in mid-lake are, similar to the inshore areas during summer, wind-driven. The response time of the mid-lake portion is probably the same as the inshore waters.

Although the winds are the primary driving force in winter, other forces exist which complicate the pattern. When a wind reversal occurs in one sector of the Lake, the remainder of the Lake is at or attempting to maintain equilibrium under the prevailing wind regime. No steady-state system can exist while external conditions are constantly changing. For this reason, Lake Michigan probably never achieves a steady-state or equilibrium condition everywhere at one time. However, large sectors, such as the southern basin, do achieve a near-equilibrium condition. Under these conditions, during the nonstratified period, a prediction model is applicable.

Current data collected over Lake Michigan were programmed to display monthly flow data in 10-degree intervals in direction and 3-cm/sec intervals in speed in a two-dimensional histogram. The total flows were grouped into 30-degree increments, i.e., 0°, 30°, 60°, 90°, etc., and the flows of the opposite angles subtracted. The result was a net or residual flow. These flows were then translated into percent so there would be continuity from one station to another.

Records of less than 1 month but more than 20 days were included. The use of the net flow value is purely relative and cannot be used to determine average speed or varying local flow patterns. The data show the long term flow in any single area and effectively mask out the rotary summer flows. The histograms can be used to disclose the normal flow at each station.

The net winds were computed for land stations at Green Bay, Milwaukee, Chicago, and Grand Haven. These were used in addition to the wind measurements made on the Lake, and are superimposed on the monthly maps.

Flow lines have been used to connect one region with another. Liberty was taken to smooth out minor differences between stations and to use conformal flow along the boundaries to the best conformance with the data. Data for the maps are normally from the current meters at the 10- and 15-meter depths.

A hydrostatic head on the Lake is produced by an excess of inflowing water which makes the Lake surface higher than its outlet. This head is present throughout the entire vertical column of water, but only the volume above 35 meters (the depth of the sill of the outlet) is affected by an outflow. The Michigan-Huron seiche, on a short-term basis, will exceed the normal outflow by more than two orders of magnitude. Net circulation patterns in the vicinity of the Straits of Mackinac are no doubt affected by the seiche. The permanent head, however, is always present in the entire Lake. Although minor, the head will exert a continual south to north influence.

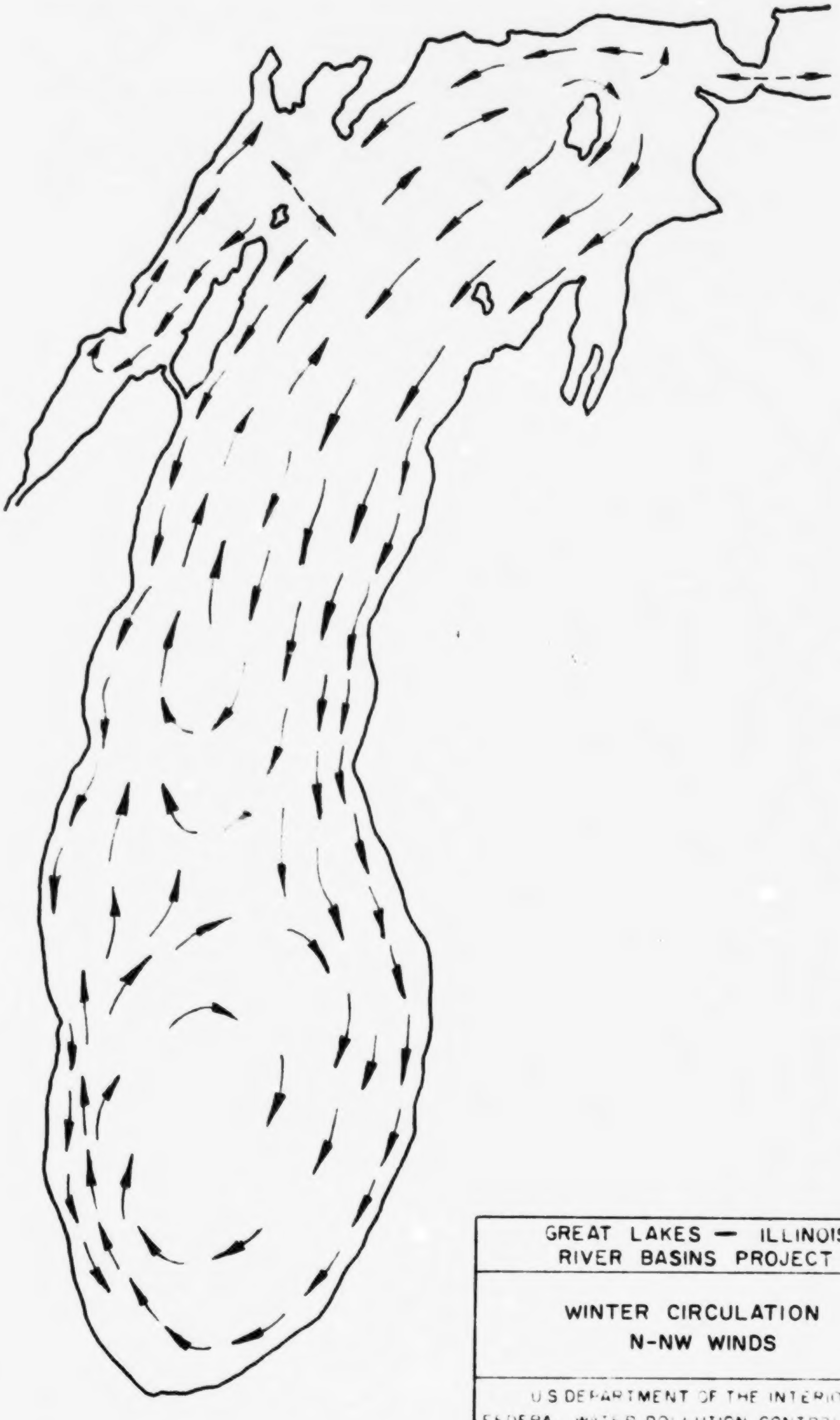
General Circulation Patterns - Surface

Two basic patterns of water movement occur in the upper layers, one in summer and one in winter. The effect of each current pattern on nearshore currents can be modified by the prevailing or net winds. The two winter patterns are shown in Figures 6-4 and 6-5. Figure 6-4 shows the influence of the north-northwest winds. The currents along the shore move southerly. This type of flow is usually found from November through March, although not necessarily continuously. It can be expected to occur about 25 to 30 percent of the year, and principally in the winter months. The mid-lake pattern, shown in both figures, is a large gyre that rotates around the basin. This rotation exists because of the prevailing wind direction. The rotation is strengthened by the southwest-northeast winds and slowed or reversed by the northwest-southeast winds.

The flow shown in Figure 6-5 represents the south-southwest winds which will occur normally from January to April, but on an intermittent basis. The shore flow is reversed from that shown in Figure 6-4. The southwest wind predominates from January to March and northeast wind occasionally occurs in April. This type of flow accounts for 20 to 25 percent of the movements during the year.

The reverse gyre does not occur with the same frequency, as the prevailing winds normally occur from the south-southwest annually and may directly influence the continuance of the rotation.

In summer, Figures 6-6 and 6-7, the shore currents again show the influence of the prevailing winds. The mid-lake flow pattern breaks down into several cells and shows more resemblance to the theoretical models of standing Poincare waves presented by Mortimer (54) and further discussed by him in Chapter 10. The generalized gyre is shown, as the cell may vary and becomes very complex. The entire circulation is dom-

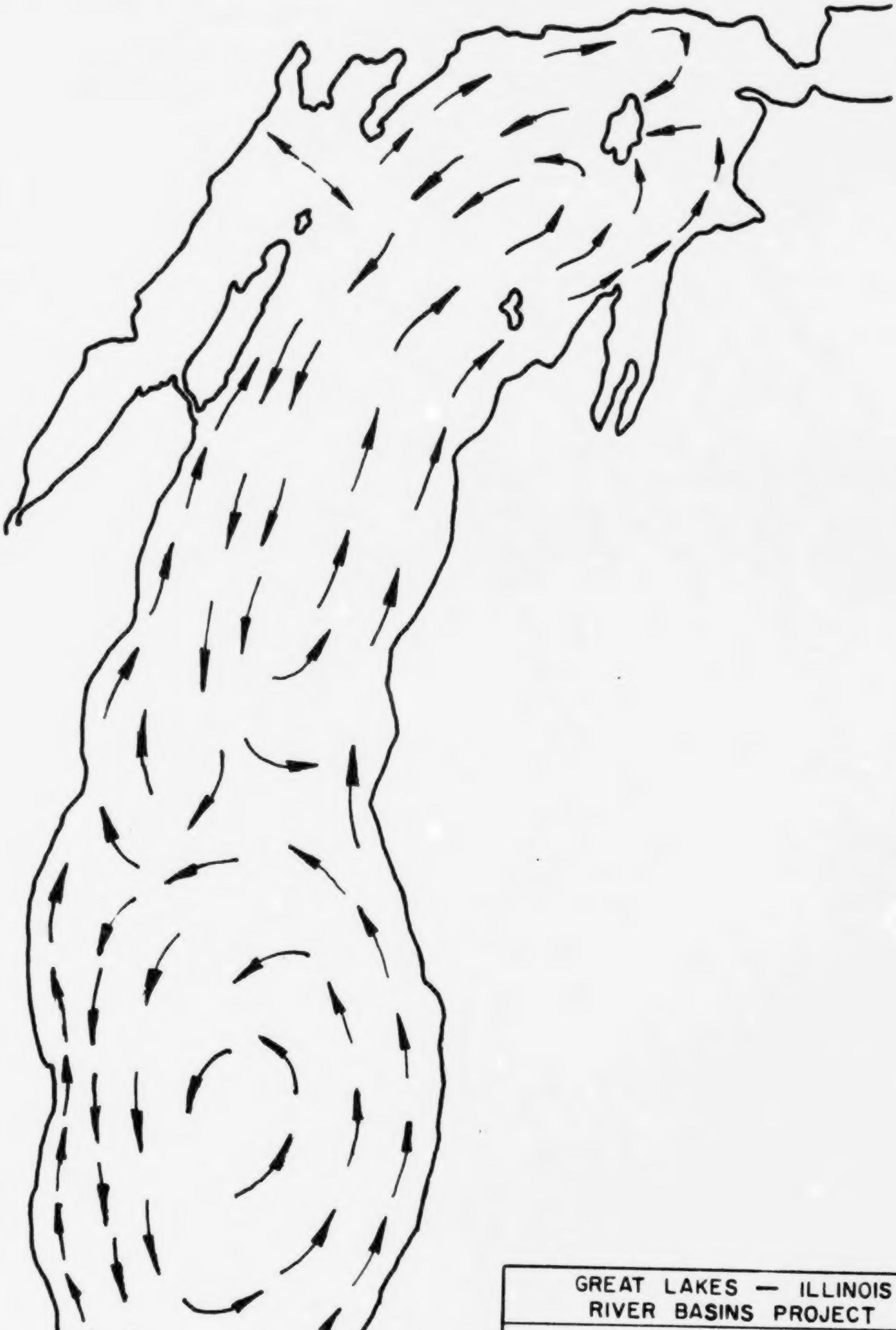


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WINTER CIRCULATION
N-NW WINDS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6 – 4

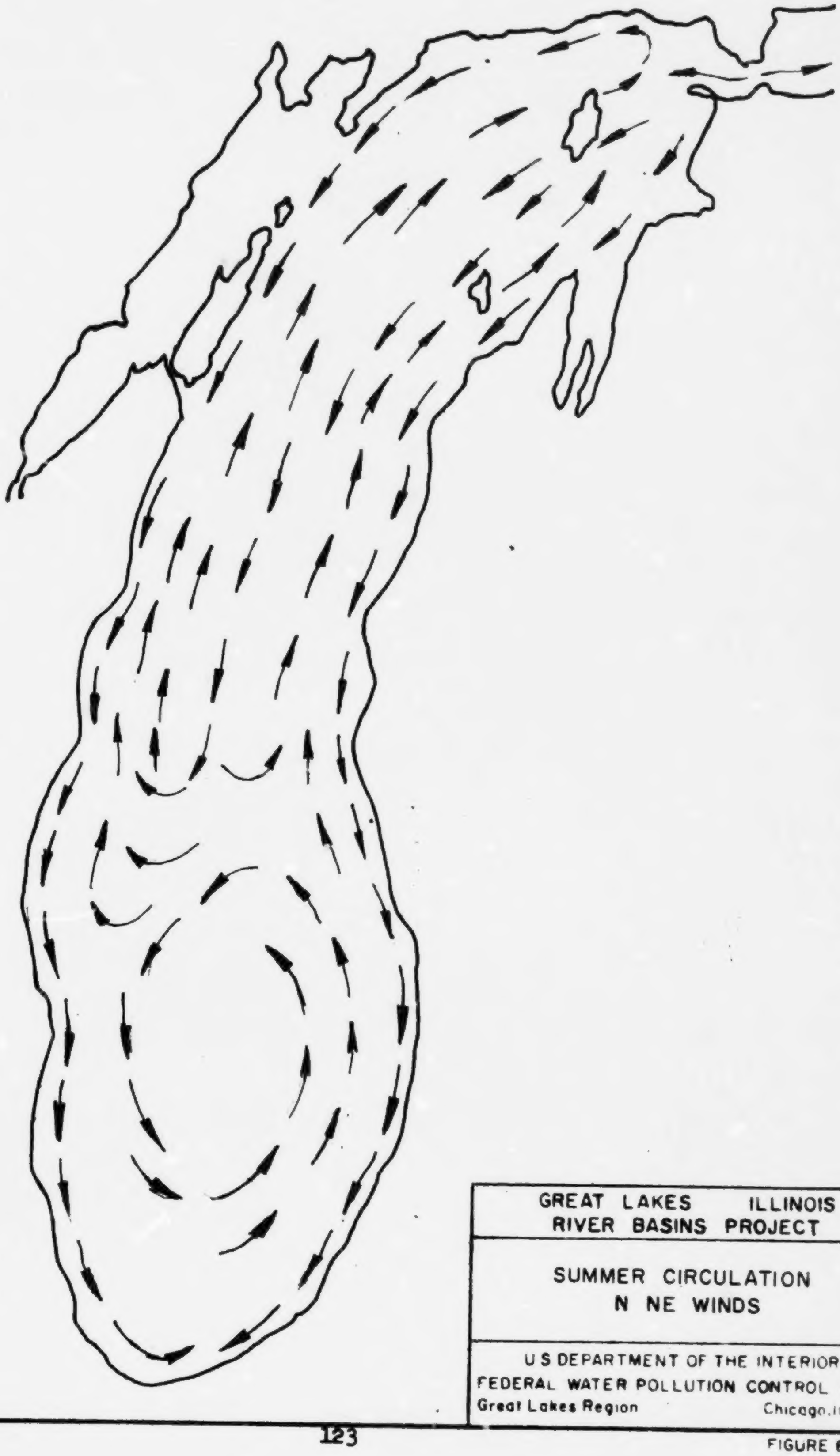


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WINTER CIRCULATION
S–SW WINDS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6–5

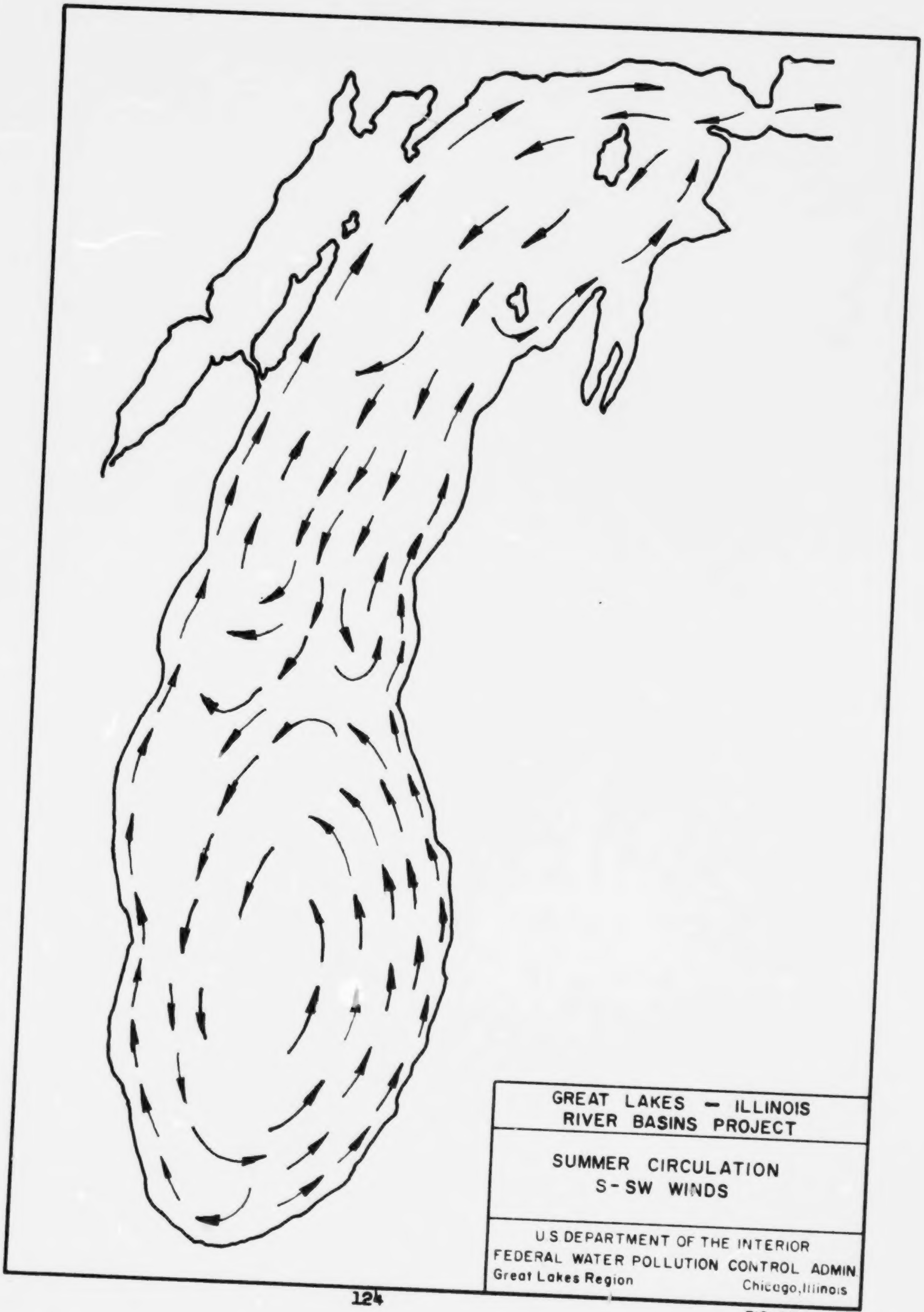


GREAT LAKES ILLINOIS
RIVER BASINS PROJECT

SUMMER CIRCULATION
N NE WINDS

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-6



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUMMER CIRCULATION
S-SW WINDS

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-7

inated by the standing internal wave pattern during the stratified period.

The break between the inshore and offshore circulation appears to occur at or near where the thermocline intersects with the bottom of the Lake. This means that the location will vary as the thermocline gets deeper. In mid-summer the location will be in the vicinity of the 15- to 20-meter contour. The circulation inshore from this "fluid" boundary is not dominated by the standing internal wave and is influenced primarily by the prevailing winds and topography. The zone between these regions is no doubt subject to unusual water movements. For instance, during calm or near equilibrium conditions, flow may be determined by proximity to a node or an antinode of an internal wave, and during storm periods the thermocline may be depressed or tilted upward and associated with the shear flows reminiscent of those found in the Atlantic Gulf Stream.

The circulation of the central portion of the southern basin in summer strongly suggests a cellular pattern, and clues to the possible nature of this have been provided by Mortimer's 1963 (54) predictions and by the observations he made to test these in Lake Michigan that year (private correspondence and paper presented at the Tenth Conference on Great Lakes Research, Toronto, April 1967, to be published in detail). These observations supported by the Office of Naval Research, took the form of the current measurements at anchor station, already described, in mid-lake off Milwaukee (from M. V. Cisco, of the U. S. Bureau of Commercial Fisheries) and detailed bathythermograph studies of the temperature distribution in the Milwaukee-Muskegon cross section. With facilities made available by the Grand Trunk and Western Railroad, bathythermograph casts were made routinely every 6 minutes (approximately every 2 km) from the company's car ferries on their regular crossings. Over the interval July 14 through August 30, 80 cross sections of temperature distribution were plotted (not all complete because of rough weather or instrument breakdown) down to a depth of 55 meters which includes the upper part of the hypolimnion. The results of this study, which are now being presented in a detailed report to the Office of Naval Research, show large depth oscillations of the thermocline often coupled with "upwelling" on one shore and "downwelling" on the other. The gradient was relatively gentle when the observations began in mid-July, but later became much sharper, particularly after strong northerly winds on August 13 which set up a striking pattern of internal standing waves across the basin, see Chapter 10, Figures 10-1 and 10-2.

Although these figures do not represent synoptic pictures because the vessel's crossing takes approximately 6 hours, they do disclose the main features of the standing wave pattern, because the car ferries pass the mid-lake position at roughly every 8 or 9 hours, or approximately every half-period of the predicted 17-hour internal wave. A mid-lake node at 66 km from Milwaukee clearly persisted for 5 or more days after the August 13 storm, and there is also evidence, less clear, of a trinodal standing wave, probably combined with the uninodal oscillation (Figure 10-2). Because the effect of a strong wind disturbance is normally to produce upwelling of the thermocline on one shore and downwelling on the other, the number of transverse nodes for the resultant internal wave must always be an odd number; and it is probable that systems with 1, 3, and perhaps 5 nodes will be the ones most frequently encountered, often with a mixture of all three in varying proportions according to the initial conditions. This will, of course, make the interpretation of any actual event complex; and it is only during relatively simpler periods, like the one which occurred after the August 13 storm, that the main factors controlling the flow pattern can be described with reasonable certainty.

If the standing wave patterns (Figures 10-1 and 10-2) are interpreted, as Mortimer has done, in terms of standing Poincare waves, then this implies that there must also be a nodal structure along the length of the basin to satisfy the boundary conditions at the ends. It was not possible, in 1963, to obtain much evidence on the characteristic dimensions of the north-south internodal distances, but there were indications that these might be roughly twice as long as those observed on the east-west cross section. If this is confirmed by research, then the circulation cells associated with the internal waves will be elongated in the north-south direction, but it should be emphasized that if several longitudinal and transverse nodalities are present, the pattern will be a complex one except during particularly simple episodes. No doubt some nodalities will be commonly preferred, and patterns characteristic for the Lake will recur from time to time.

It should also be emphasized that Mortimer's relatively simple model of the super-position of Poincare (progressive and standing) and Kelvin (progressive) wave solutions have been chosen to apply to the central portion of the Lake, between 42° and 44° north, which comes close to a rectangular north and south channel. For conditions near the ends of the basin, which the Project's studies also covered, the following mathematical models may prove to be more appropriate: the semi-circular model (involving Bessel functions) closing the end of a long channel, or a high-eccentricity elliptical model (involving Mathieu functions).

The results from the current meters provide overwhelming confirmation that waves of near-inertial frequency are the dominant features of the circulation of the mid-lake area of Lake Michigan during the period of stratification from early spring right through to

November. In mid-winter, when a deep winter (reversed) thermocline is present, the effects of internal waves on the currents can also be identified. Two of the best documented examples of internal wave effects are provided by stations 8 and 9 where the temperature and current data were more complete during the summer of 1963 than at other stations. These stations are approximately 35 km apart, and one series of measurements between August 19 and August 24, 1963, showed that, with the top of the thermocline at about 20 meters, the currents at 15 and 22 m were always in opposite phase to each other. Also, for short intervals, the currents at any given depth at both stations were in phase, suggesting that there was no node (or an even number of nodes) between them.

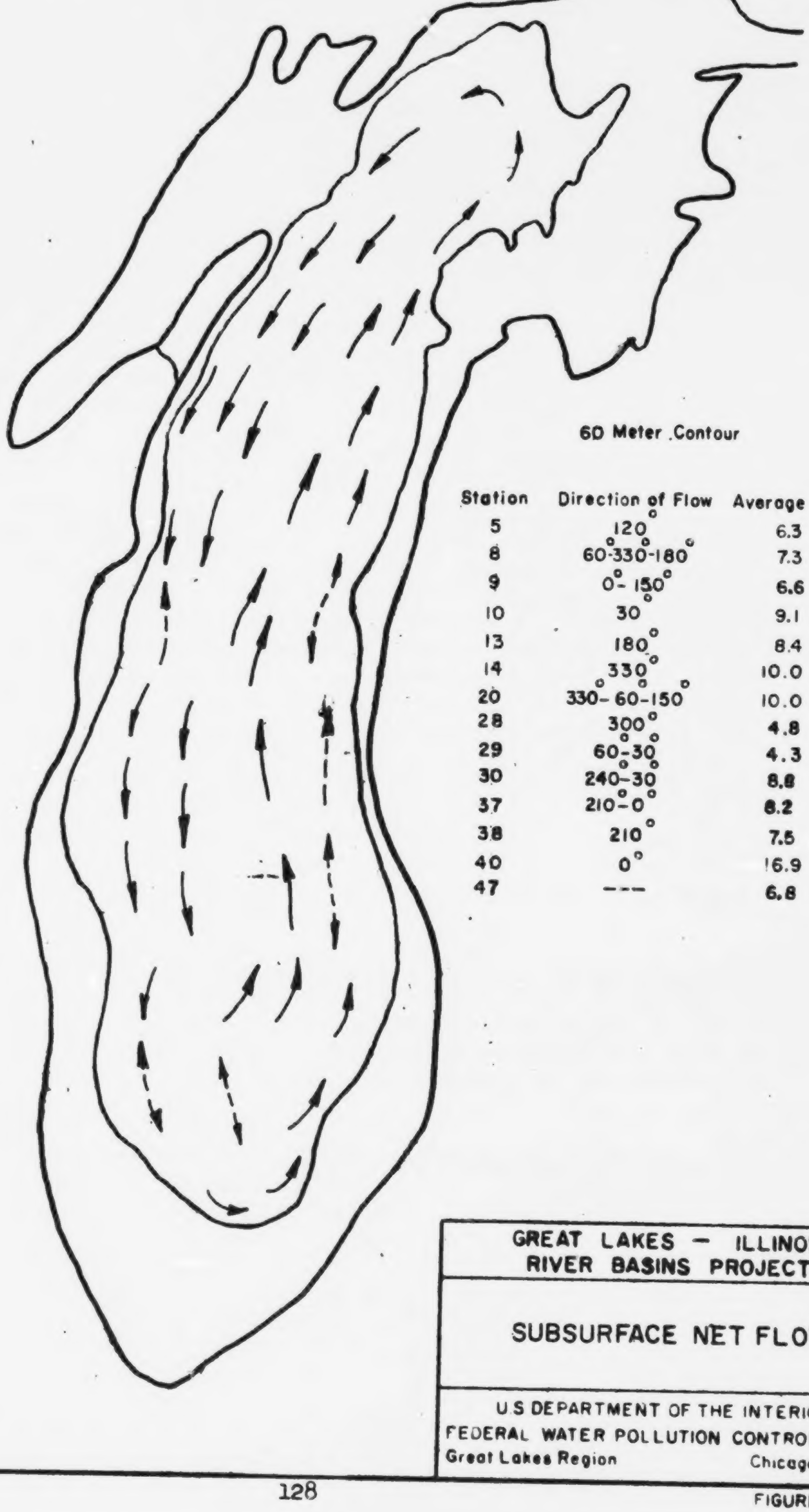
General Circulation Patterns - Subsurface

Figures 6-8 to 6-14 describe what appears to be the general circulation found in the layers from 60 to 240 m. The general pattern appears to be a counterclockwise rotation through all the layers and very dominant near the bottom. Due to the smaller number of stations in the subsurface layers, they were grouped together to form one map for each level. Where net flows reversed at a station, the data are included on the table with each figure. Although the counterclockwise pattern prevails, it is by no means a permanent circulation. At least to 180 m there are several instances at each depth level to show that the pattern reverses. At the 210-m level and below, however, the net flow pattern may be more stable. The day-to-day movements suggest that there is as much variability at 240 meters as at the 10-meter level. In summer and winter the rotary component of the horizontal flow patterns, due to the internal wave on the thermocline, was found at the 240-meter level, portraying movements very similar to surface movements in the summer.

Figure 6-8, for 60 m depth, suggests that the subsurface flows move across the bar region. Some of the stations indicate that the net flows can be in the opposite direction and reverse patterns no doubt can occur. Since the stations include data collected under all types of external forces, it is understandable that reverse patterns can exist.

On Figure 6-9, at the 90-meter level, the counterclockwise pattern again is demonstrated. The ridge is clearly evident and two pockets are defined. Several stations still indicate that reverse patterns are present.

At 120 meters, Figure 6-10, the Lake is divided into two parts. The south basin and the north basin apparently rotate in the same direction although reversal is still evident from the data, especially



60 Meter Contour

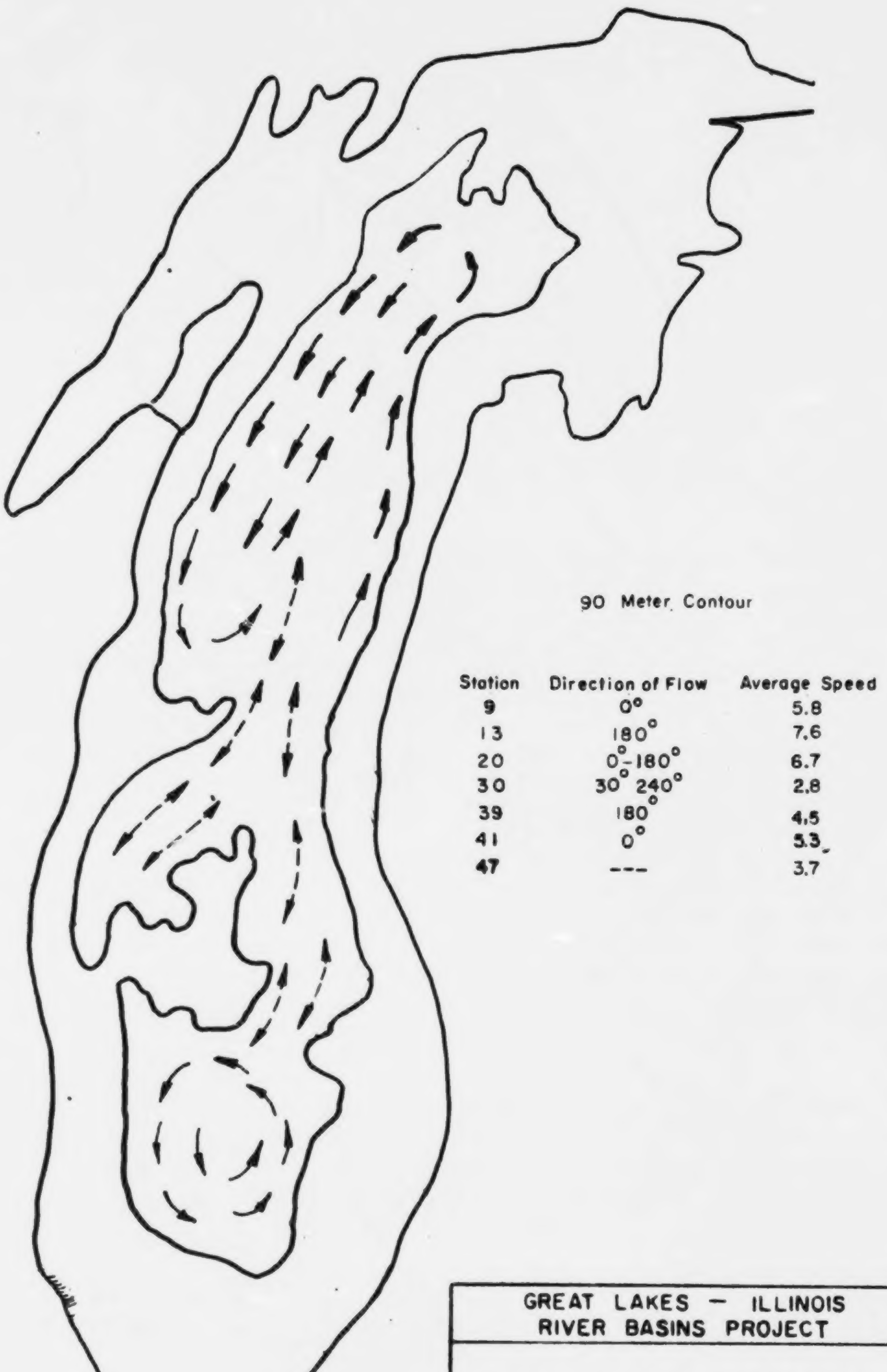
Station	Direction of Flow	Average Speed
5	120°	6.3
8	60°-330°-180°	7.3
9	0°- 150°	6.6
10	30°	9.1
13	180°	8.4
14	330°	10.0
20	330°- 60°-150°	10.0
28	300°	4.8
29	60°-30°	4.3
30	240°-30°	8.8
37	210°-0°	8.2
38	210°	7.5
40	0°	16.9
47	---	6.8

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-8



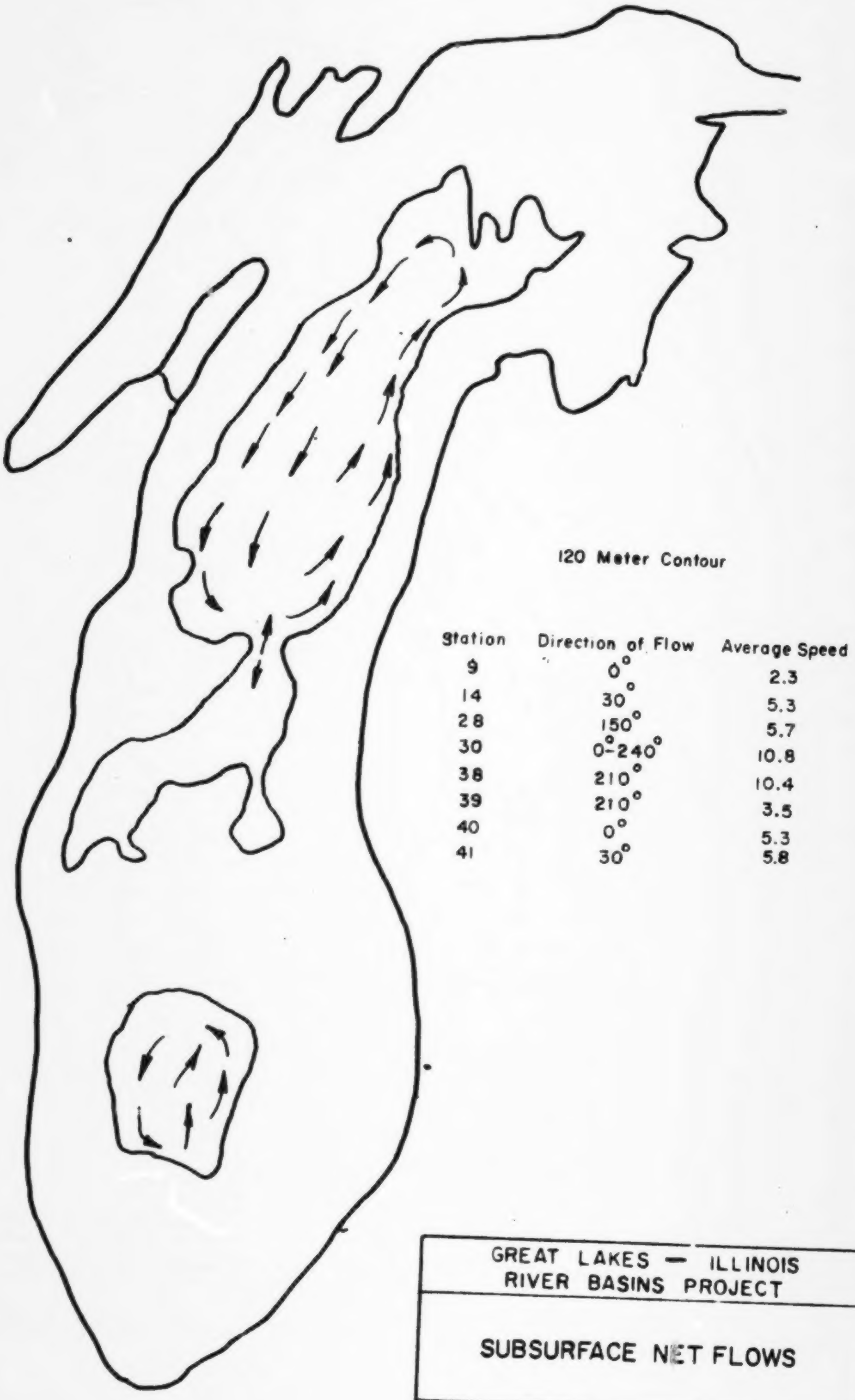
Station	Direction of Flow	Average Speed
9	0°	5.8
13	180°	7.6
20	0°-180°	6.7
30	30° 240°	2.8
39	180°	4.5
41	0°	5.3
47	---	3.7

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-9



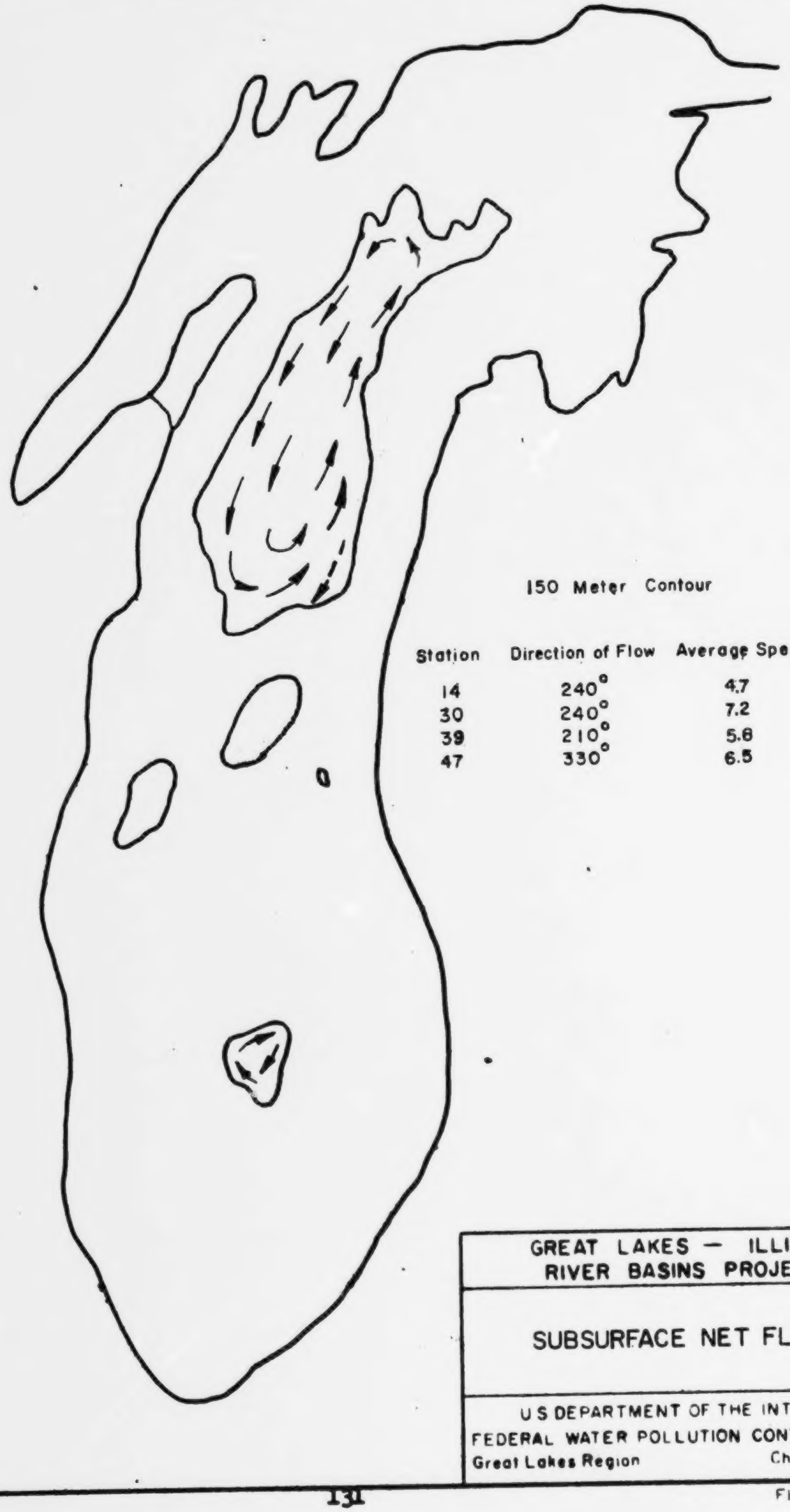
Station	Direction of Flow	Average Speed
9	0°	2.3
14	30°	5.3
28	150°	5.7
30	0°-240°	10.8
38	210°	10.4
39	210°	3.5
40	0°	5.3
41	30°	5.8

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6—10



150 Meter Contour

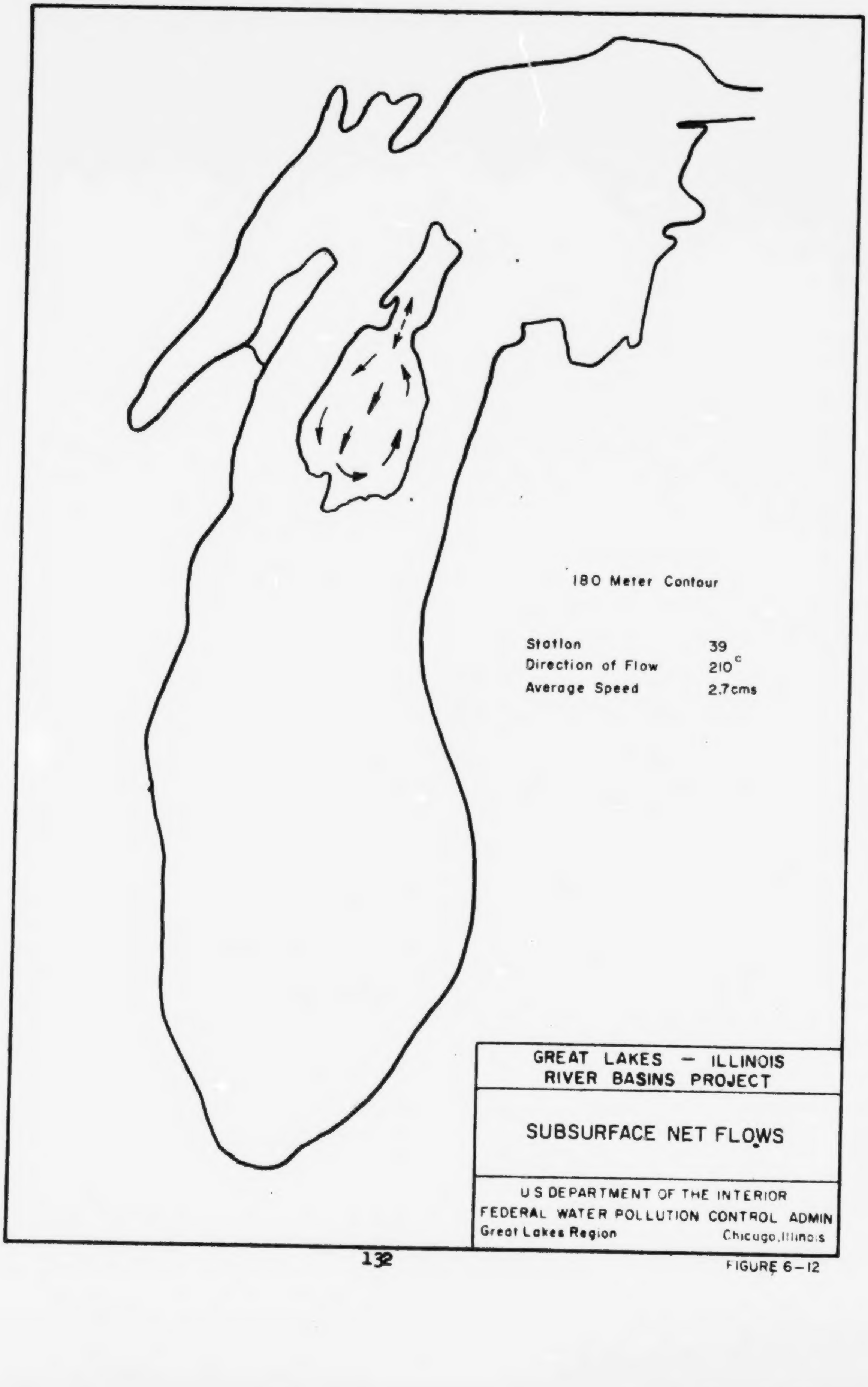
Station	Direction of Flow	Average Speed
14	240°	4.7
30	240°	7.2
39	210°	5.8
47	330°	6.5

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-11

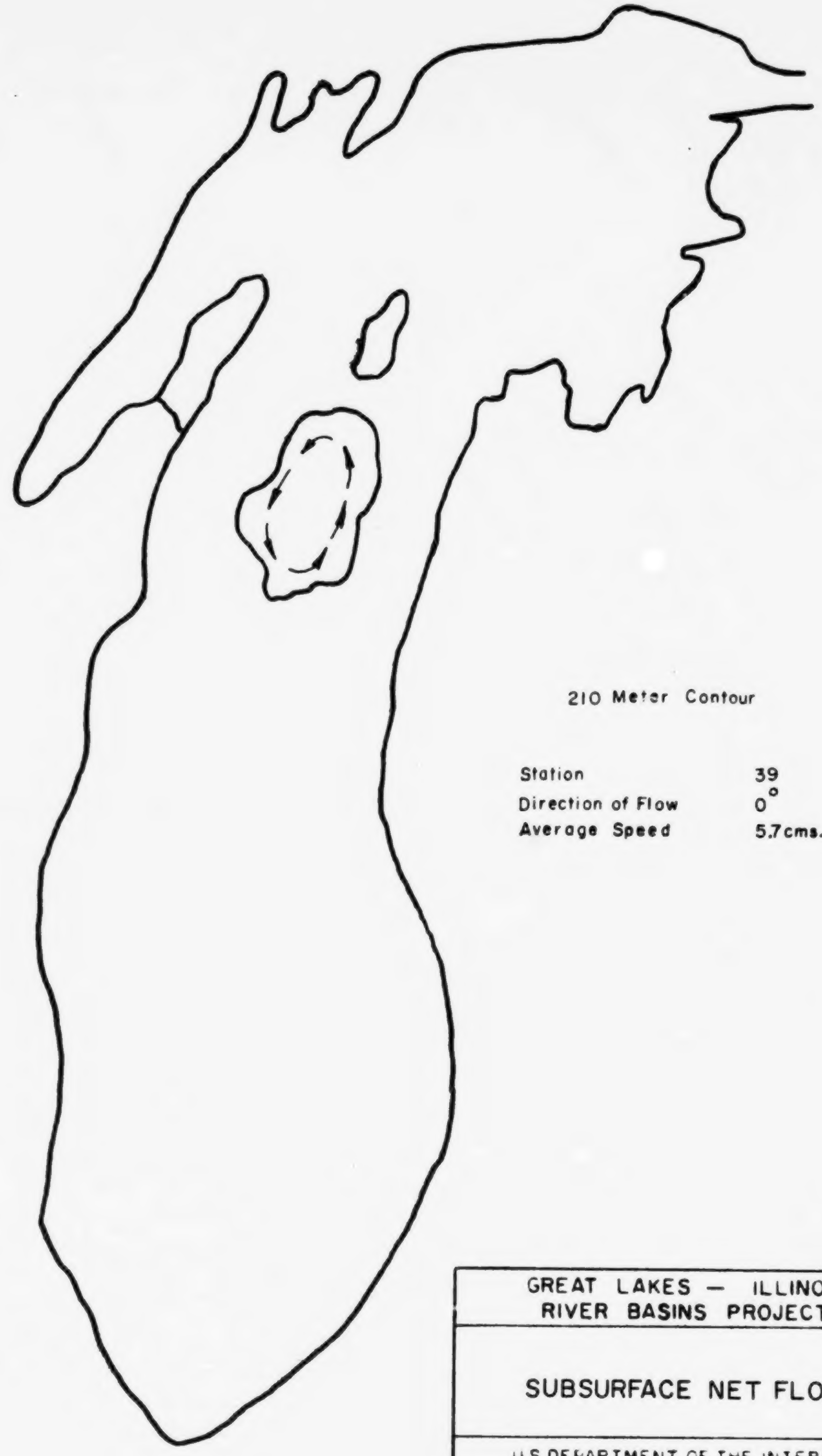

180 Meter Contour
Station 39
Direction of Flow 210°
Average Speed 2.7cms

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6–12

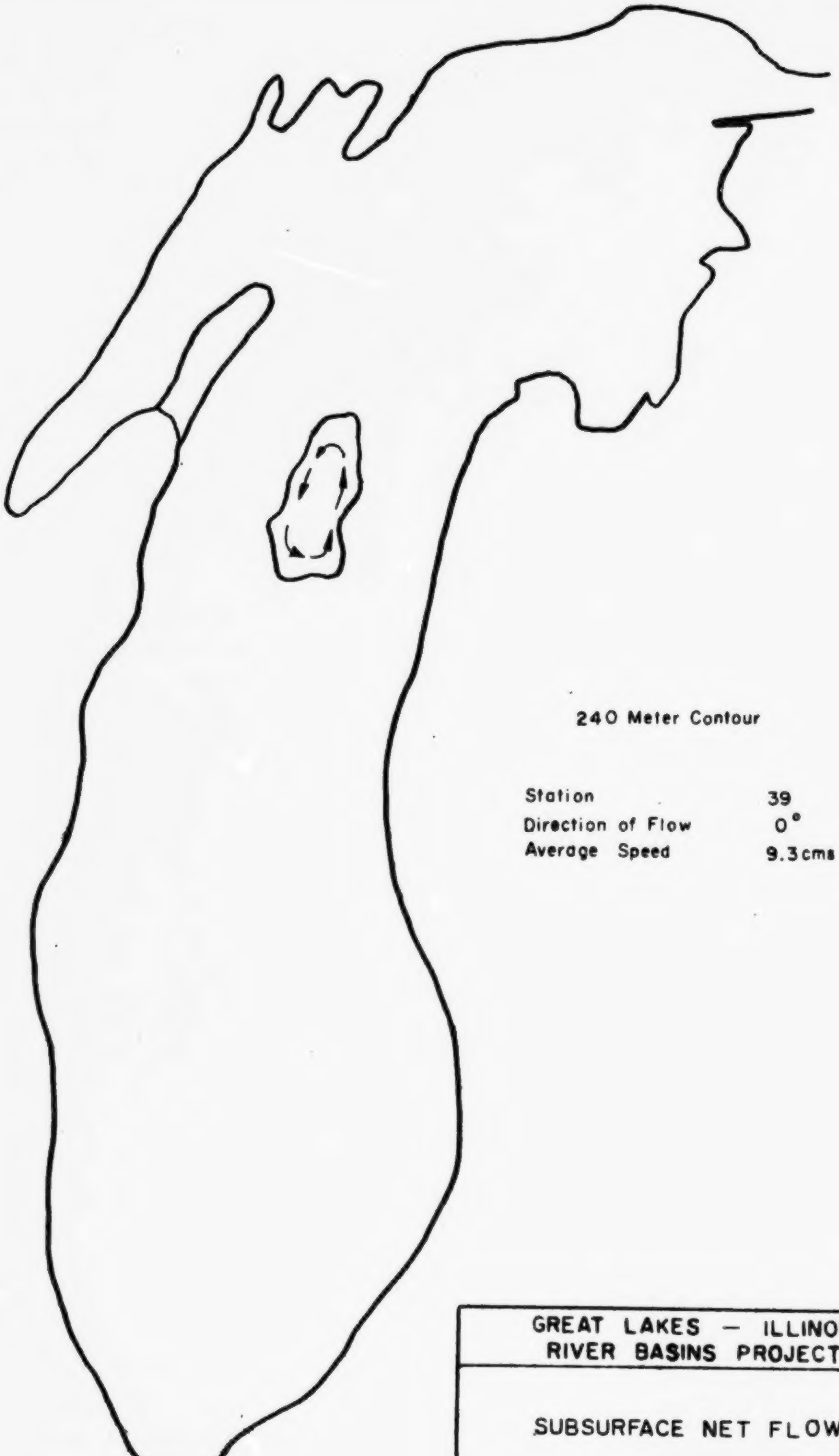

210 Meter Contour
Station 39
Direction of Flow 0°
Average Speed 5.7cms.

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6—13


240 Meter Contour
Station 39
Direction of Flow 0°
Average Speed 9.3 cms

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SUBSURFACE NET FLOWS

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-14

in the north basin. There is a hint from station 14 that the south end may have two gyrals occurring at the same time.

The 150-meter level, Figure 6-11, shows that reverse patterns still exist from the data at station 30. The southern basin, although now comparatively small, is still a complicated area of more than 100 square miles. It cannot be assumed that an area of such proportion exhibits such a simple pattern, because the currents are still quite complex. For the first time the pattern in the southern basin shows a clockwise circulation. The net flow was 180° out of phase from the 120-meter level.

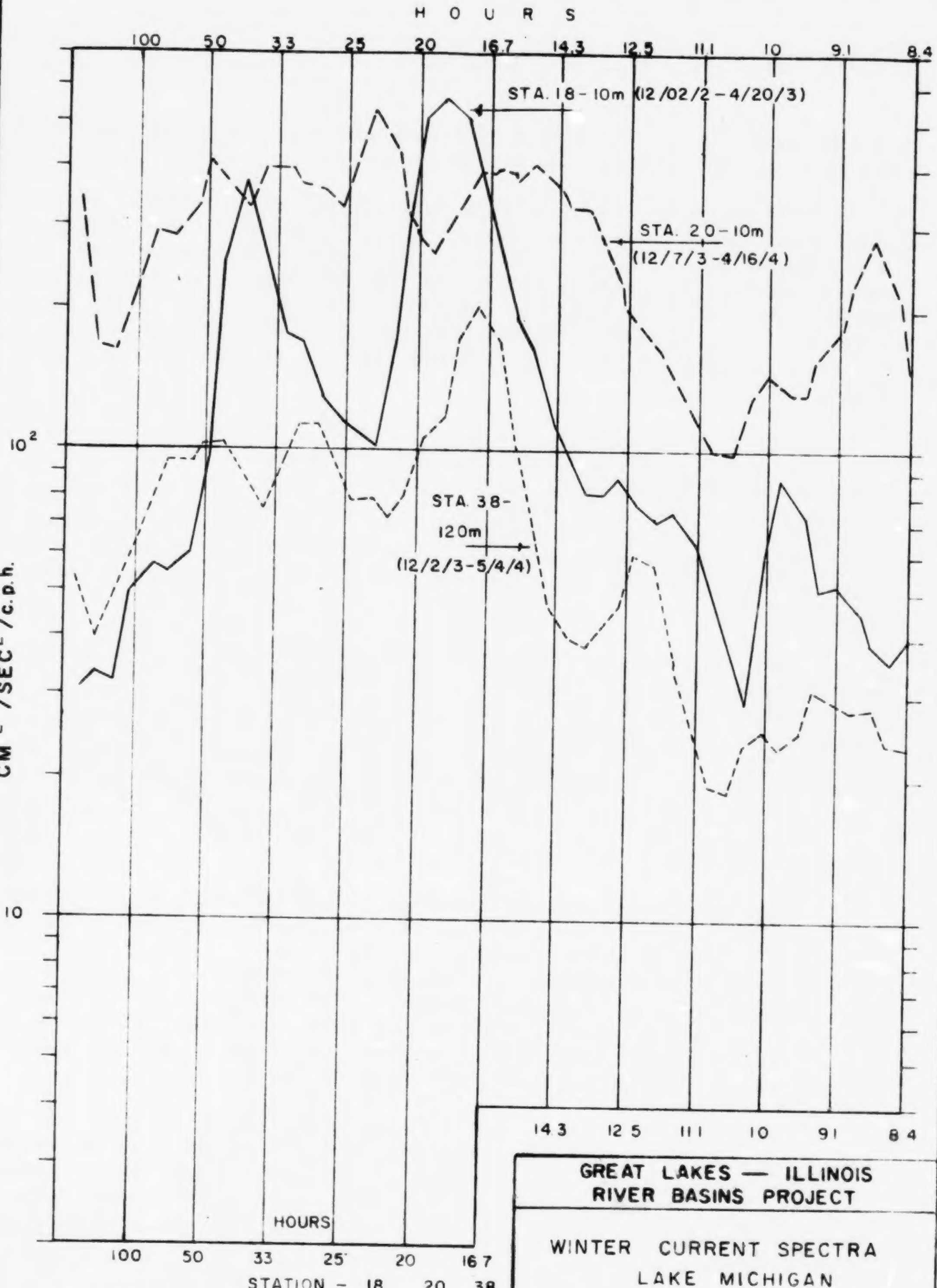
Figures 6-12 to 6-14 are based on data from the winter of 1962-63. The data indicate a counterclockwise rotation at the three depths. The data for station 39 shifts nearly 180° from the 180-meter level to the 210-meter level. The area of the basin is reduced in size between the 180-meter level and the 210-meter level. The change in shape maintains the same counterclockwise circulation pattern. Since stirring occurs to the bottom of the Lake, the lower levels no doubt can reverse direction.

The circulations just described under the heading "General Circulation," which represent flow over long periods and which can be either clockwise or counterclockwise, should not be confused with the clockwise circulation coupled with internal waves which is sharply tuned to the inertial frequency. Further examples of this, and of the effect of wind on currents and on internal waves, are given in Chapter 10.

Spectral Analysis

While the near-inertial frequency of current rotation associated with internal waves in summer is very evident for shorter or longer intervals and the records from many stations, our spectra of current data are useful in detecting this and other frequencies and facilitated the interpretation of a complex picture. The spectra presented here, covering the period November 1962 to July 1964, are summarized in Table 6-7, and selected results are depicted graphically on Figures 6-15 through 6-43. Station locations are shown on Figure 6-2.

Station 3 is located n the west shore at the southern end of Lake Michigan. The data were gathered from January 17, 1963 to March 22, 1963, at 15 meters. There are no statistically significant peaks in the speed, Vx and Vy spectra, the north-south and east-west components of the current, although there was energy in the long period disturbances.



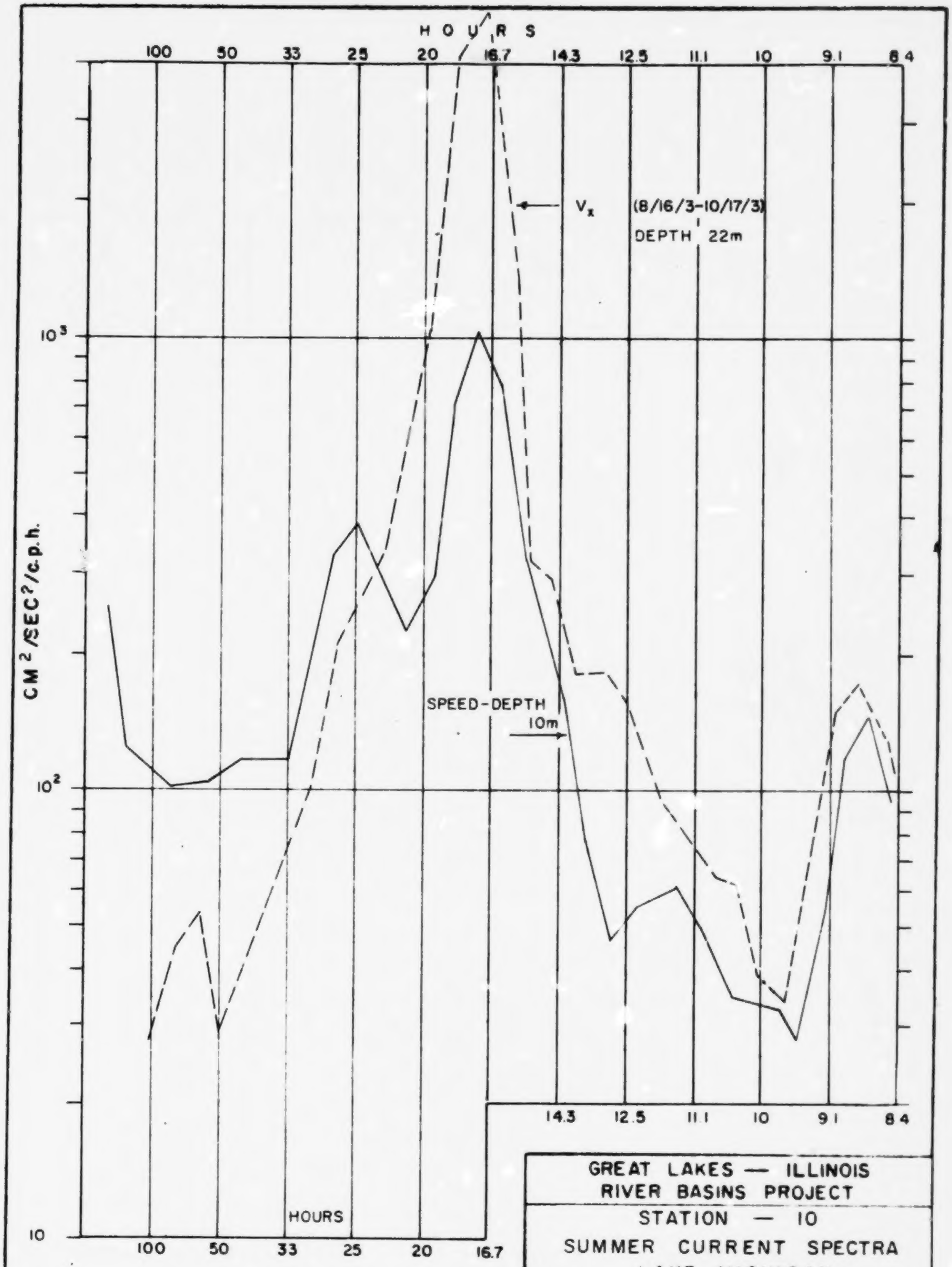
STATION -	18	20	38
DEGREES OF FREEDOM -	32	31	36
NO. OF OBSERVATIONS	-6482	6252	7316

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WINTER CURRENT SPECTRA
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-15



DEGREES OF FREEDOM - 20

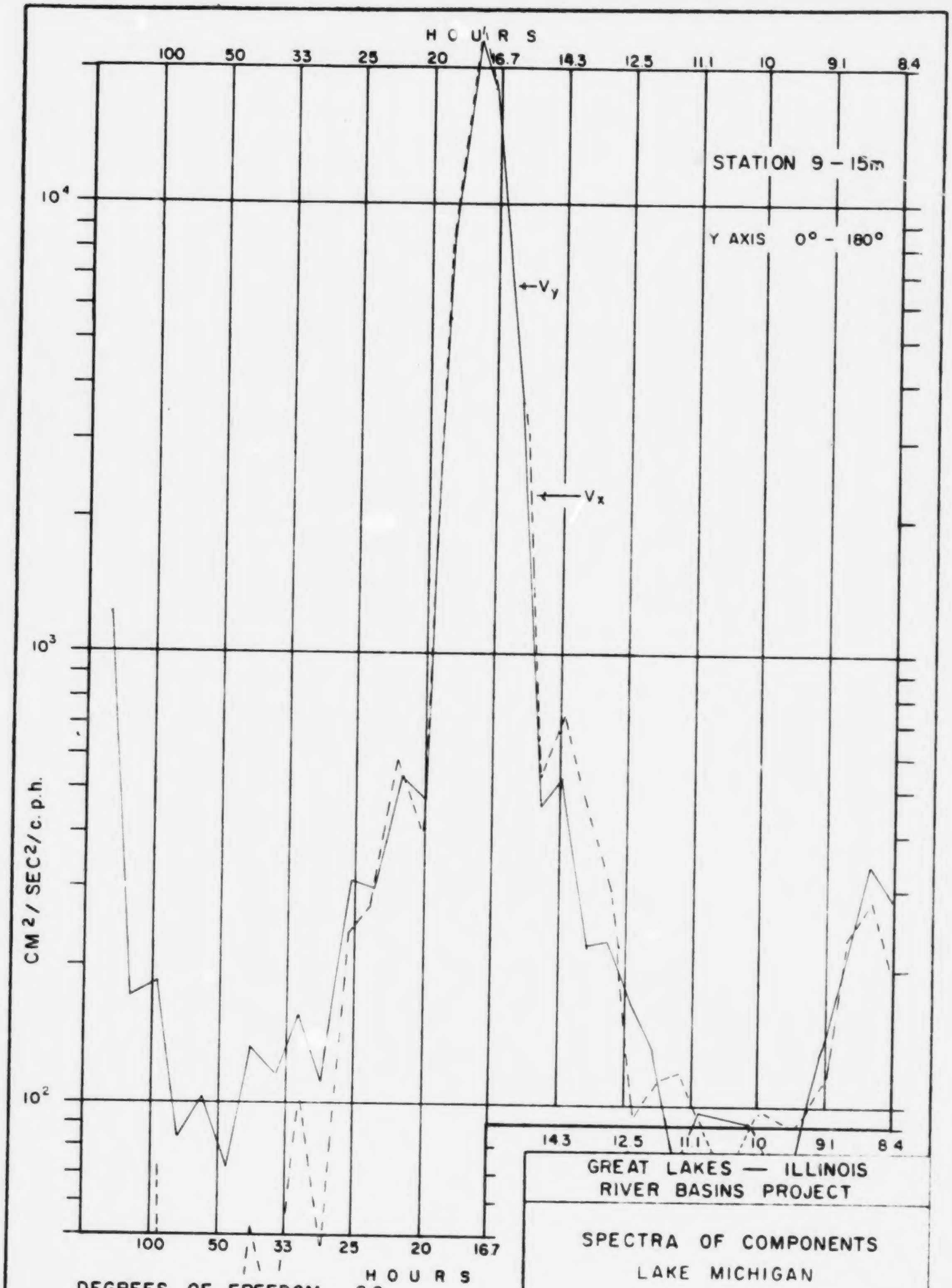
NO OF OBSERVATIONS - 4455

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STATION — 10
SUMMER CURRENT SPECTRA
LAKE MICHIGAN

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6 -16



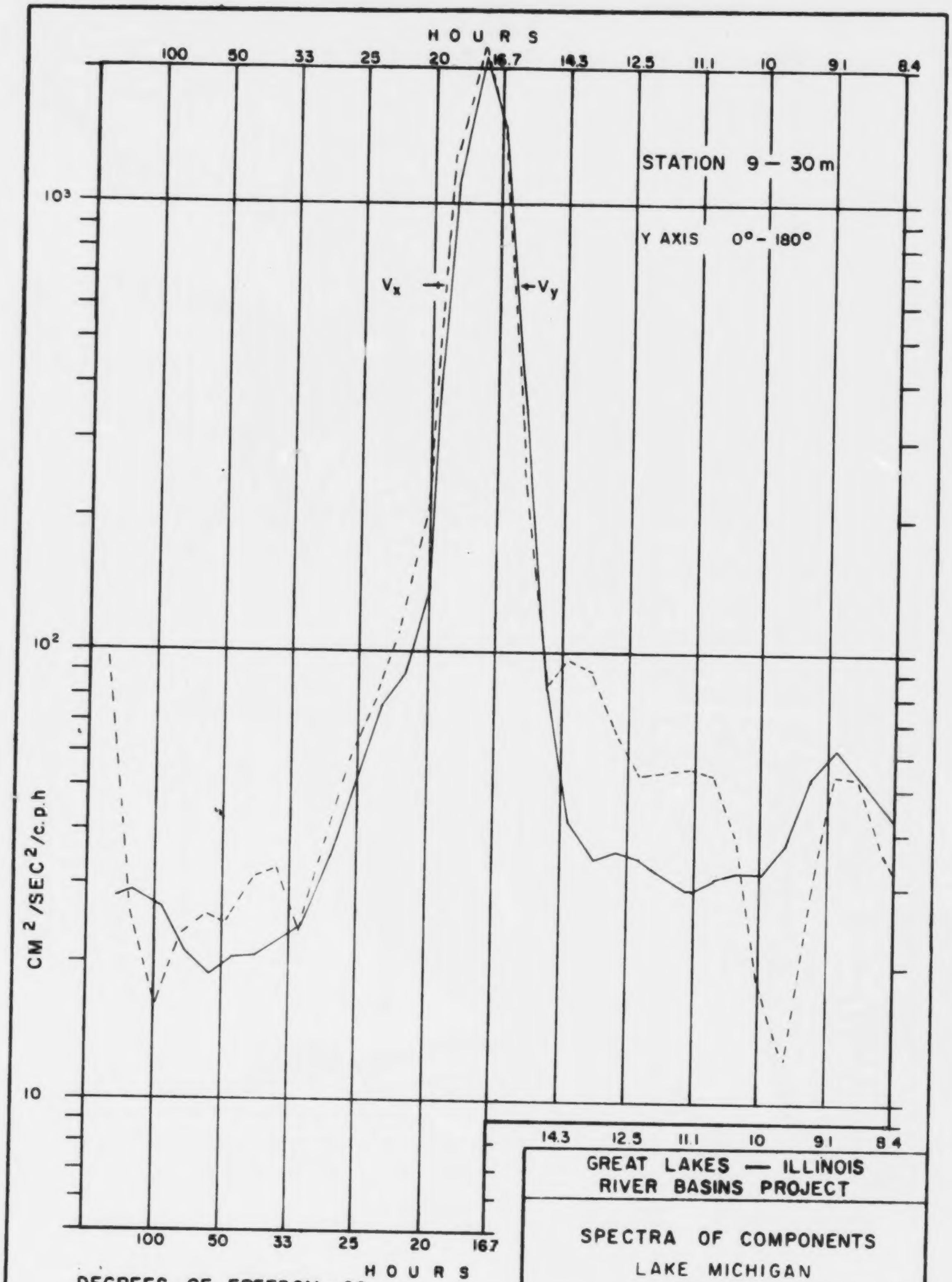
DEGREES OF FREEDOM - 20
DATE - 8/18/3-10/17/3
NO. OF OBSERVATIONS - 4312

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-17



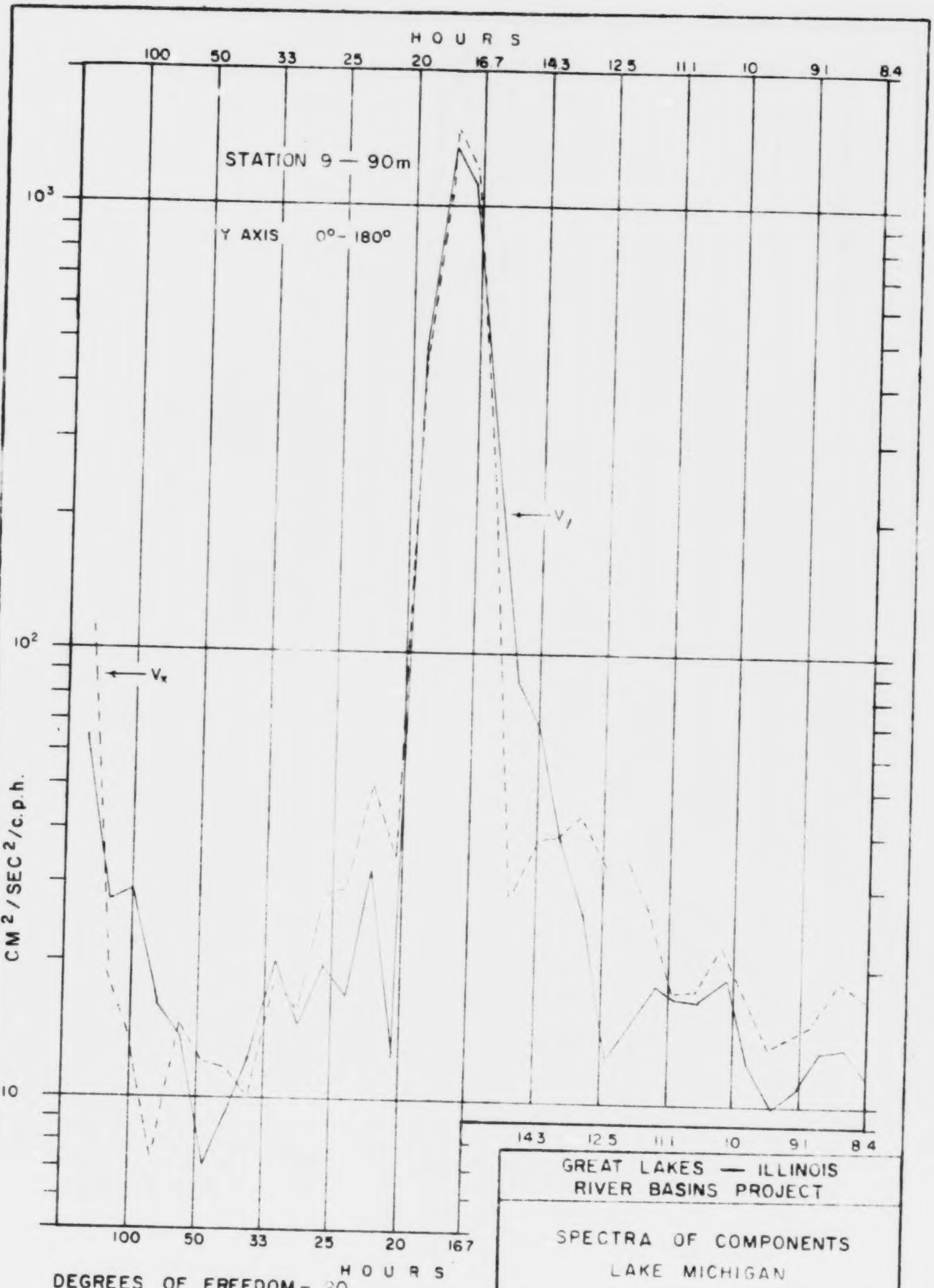
DEGREES OF FREEDOM - 20
DATE - 8/18/3 - 10/17/3
NO. OF OBSERVATIONS - 4304

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-18



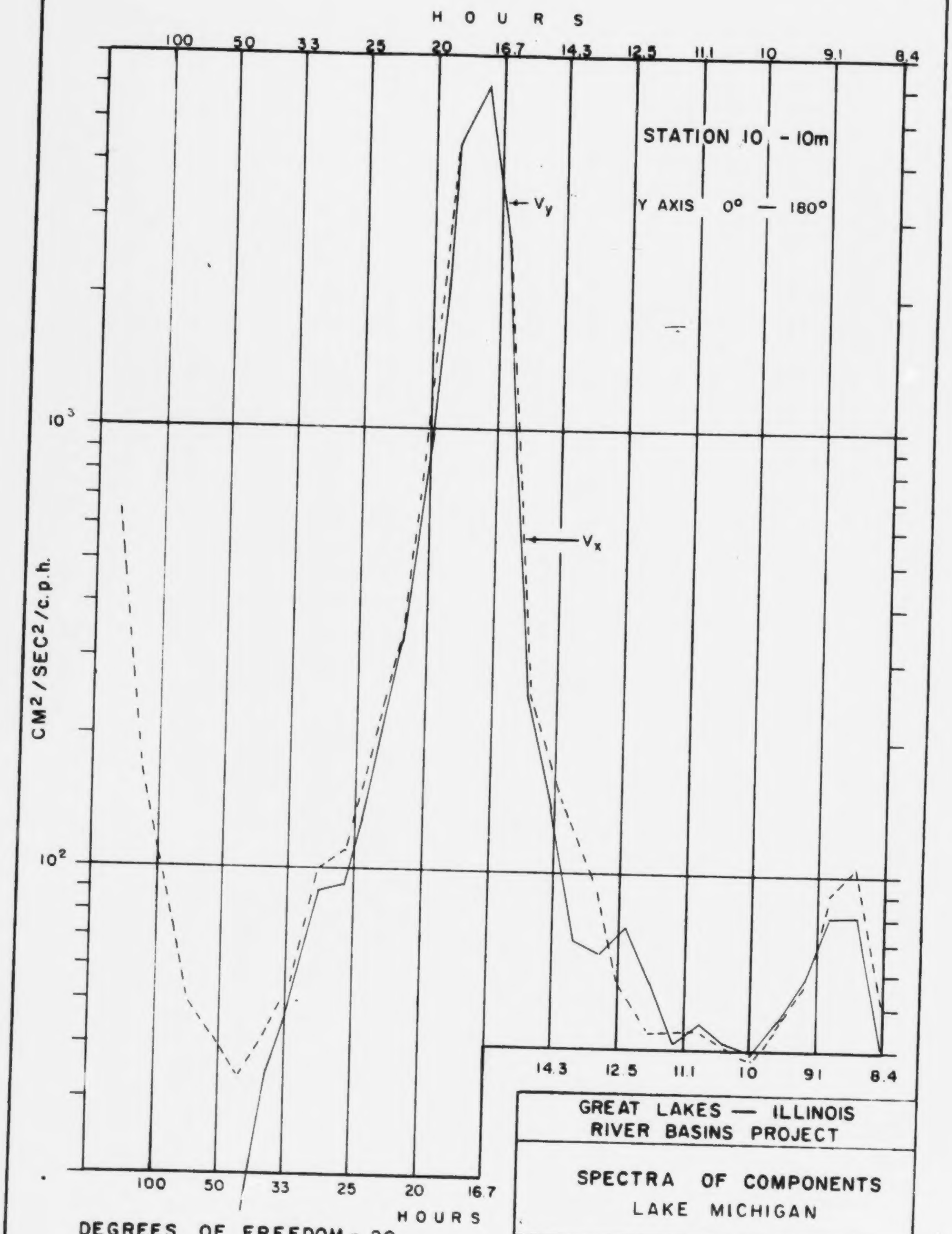
DEGREES OF FREEDOM - 20
DATE - 8/18/3 - 10/17/3
NO. OF OBSERVATIONS - 4315

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Ill.

FIGURE 6-19



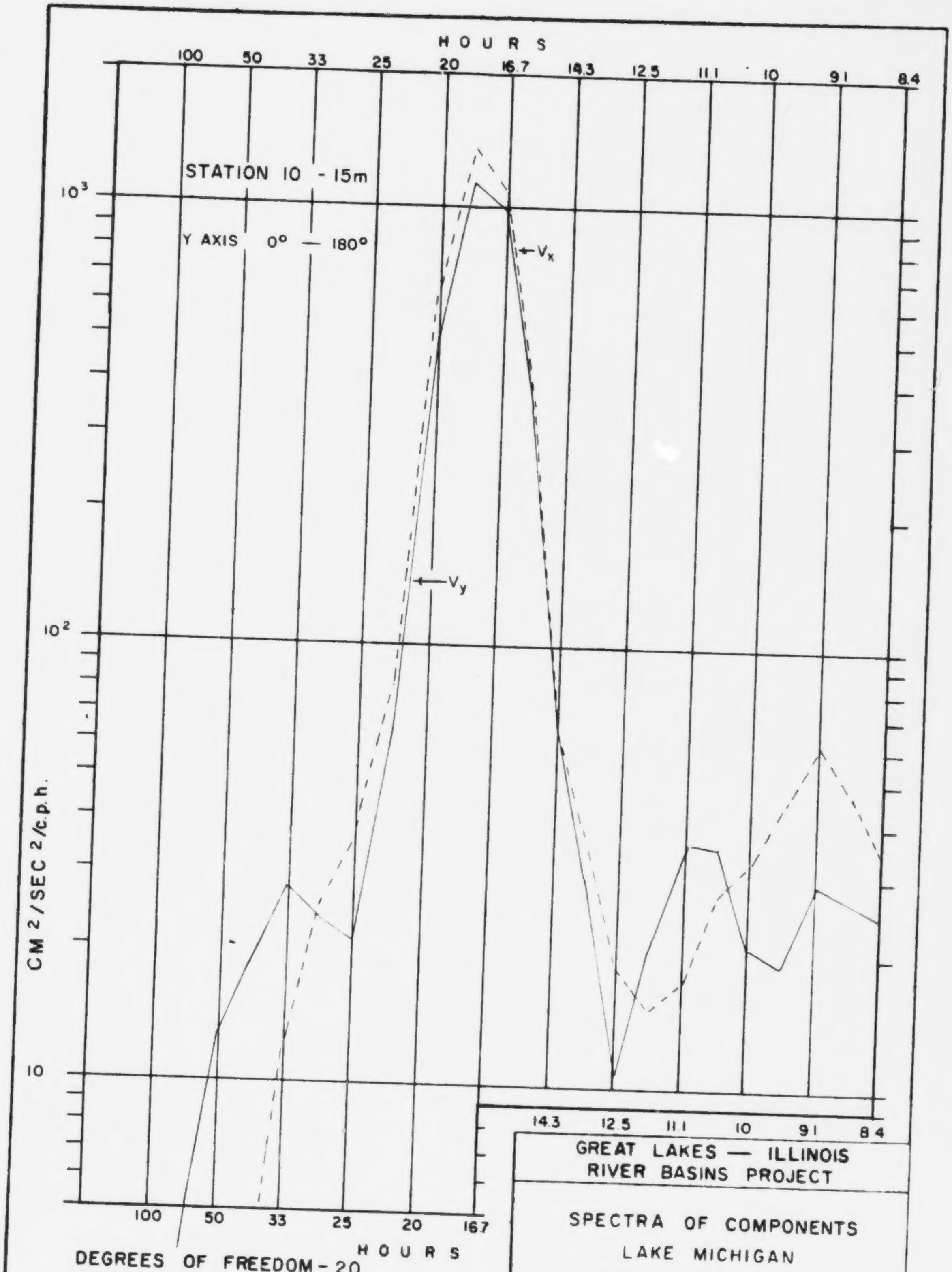
DEGREES OF FREEDOM - 20
DATE - 5/11/4 - 7/5/4
NO. OF OBSERVATIONS - 3955

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-20



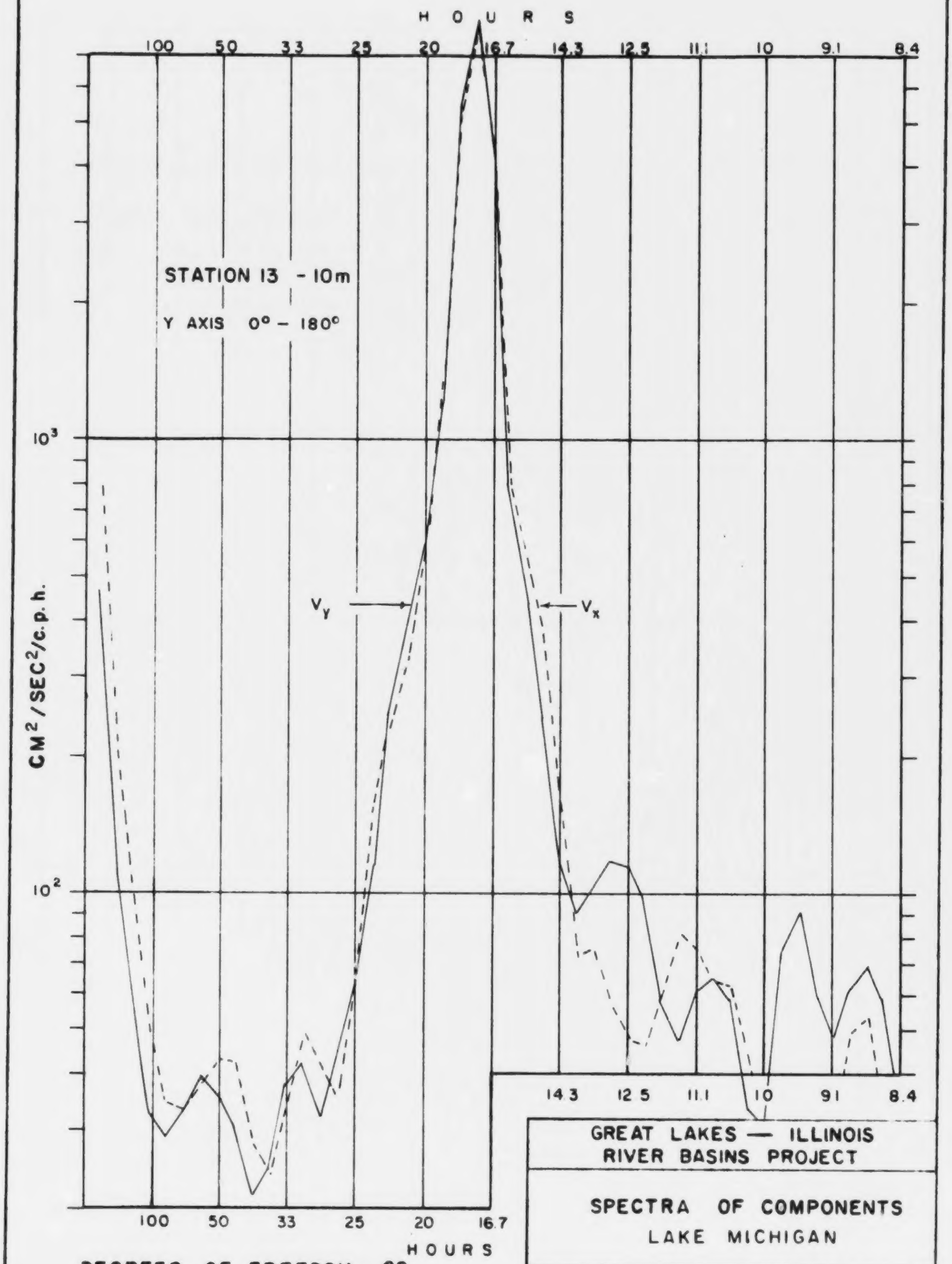
DEGREES OF FREEDOM - 20
DATE - 5/11/4 - 7/5/4
NO. OF OBSERVATIONS - 3057

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-21



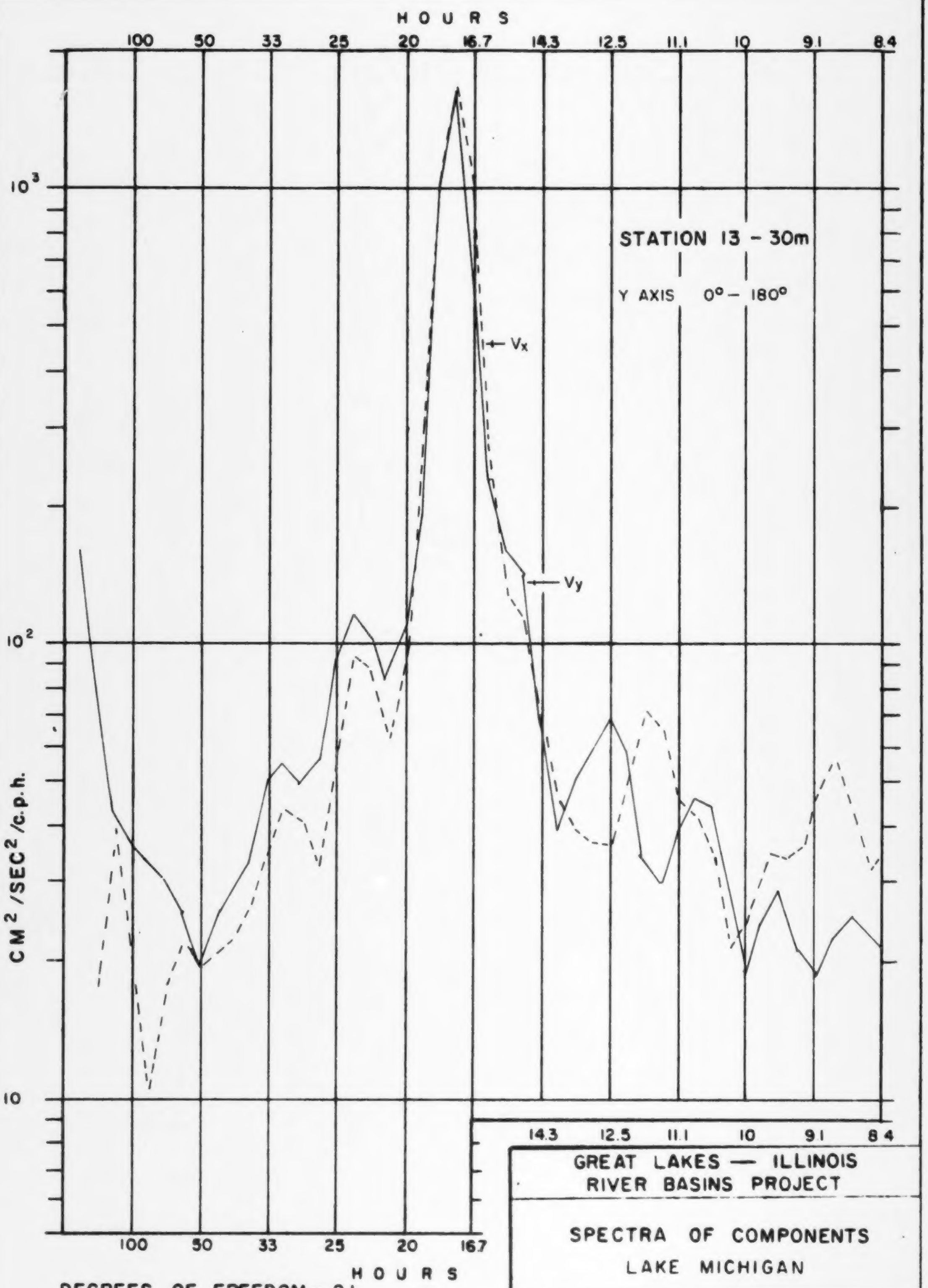
DEGREES OF FREEDOM - 20
DATE - 4/10/4 - 7/8/4
NO. OF OBSERVATIONS - 6341

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-22



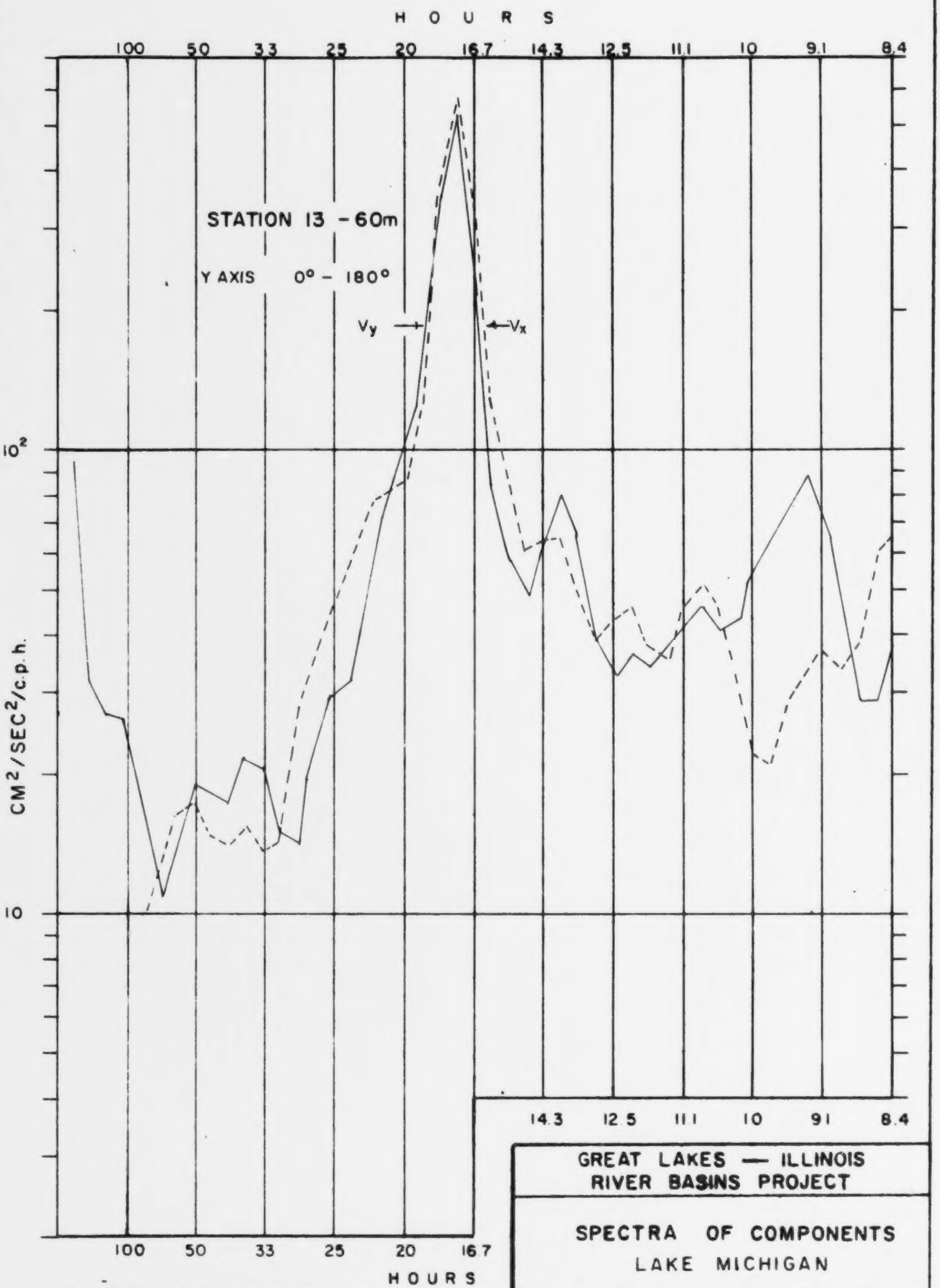
DEGREES OF FREEDOM - 21
DATE - 4/10/4 - 7/8/4
NO. OF OBSERVATIONS - 6417

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-23



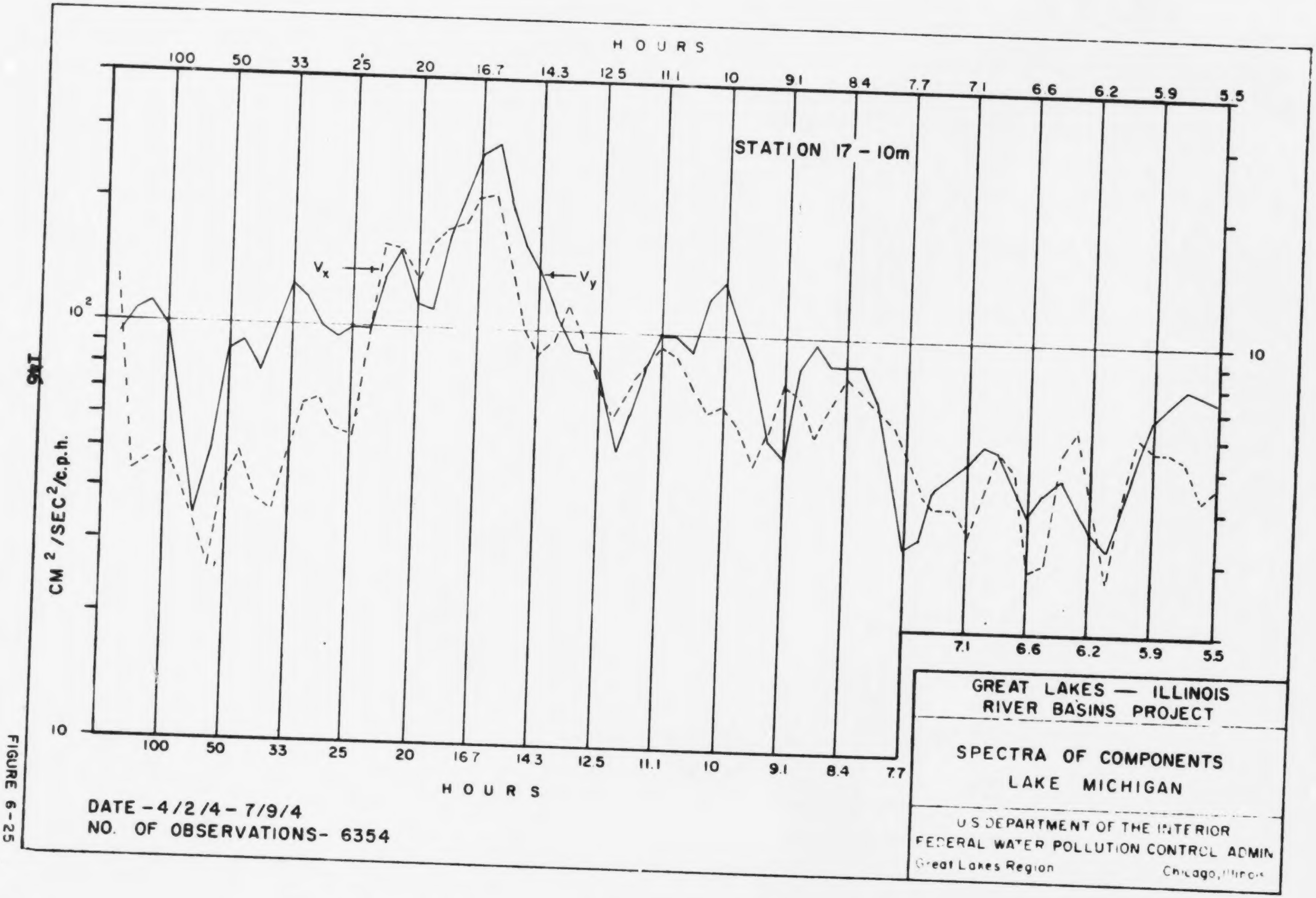
DEGREES OF FREEDOM - 21
DATE - 4/10/4 - 7/8/4
NO. OF OBSERVATIONS - 6423

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-24



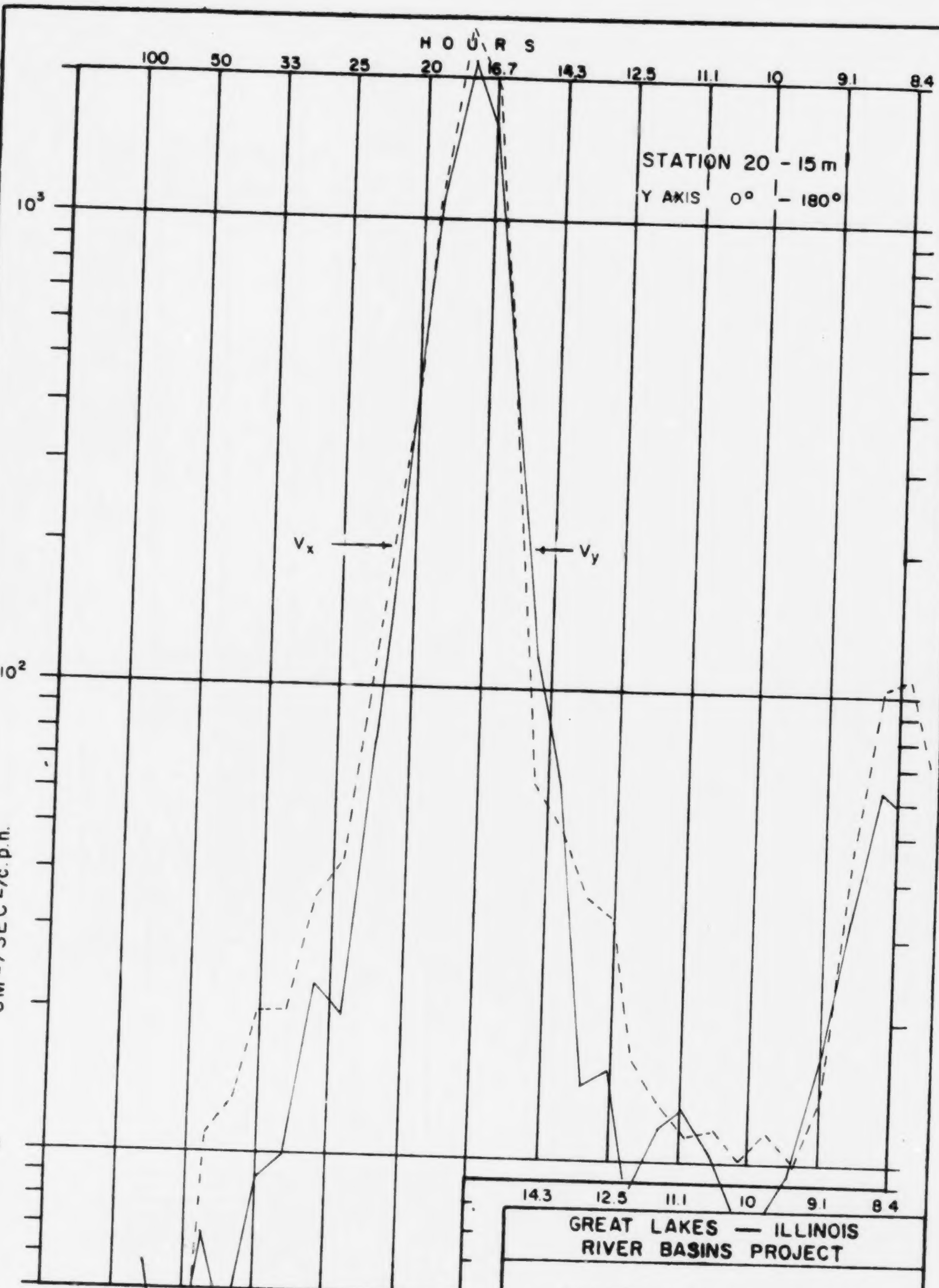
DATE - 4/2/4 - 7/9/4
NO. OF OBSERVATIONS - 6354

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-25



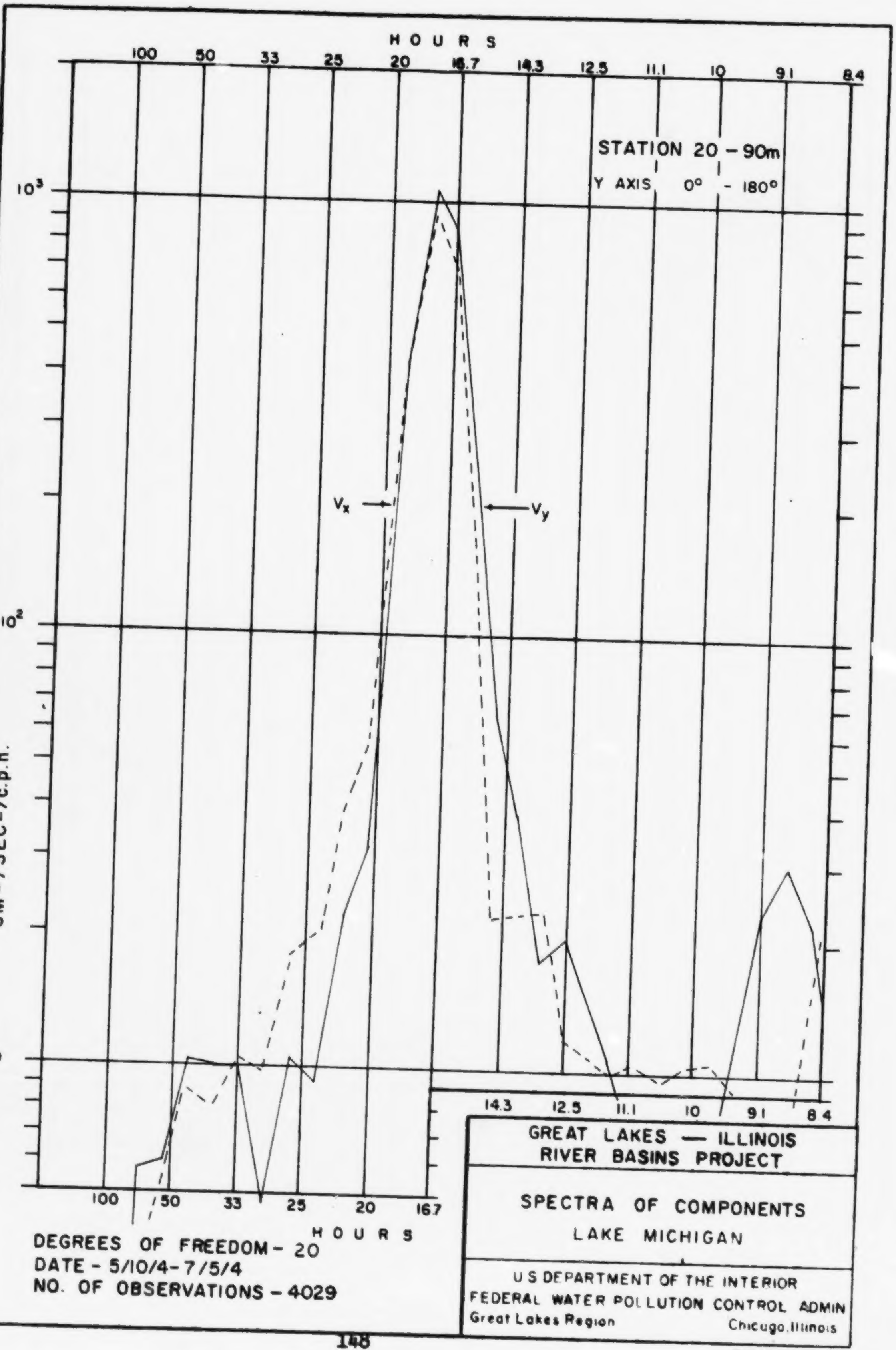
DEGREES OF FREEDOM - 20
DATE - 5/10/4 - 7/5/4
NO. OF OBSERVATIONS - 4029

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-26



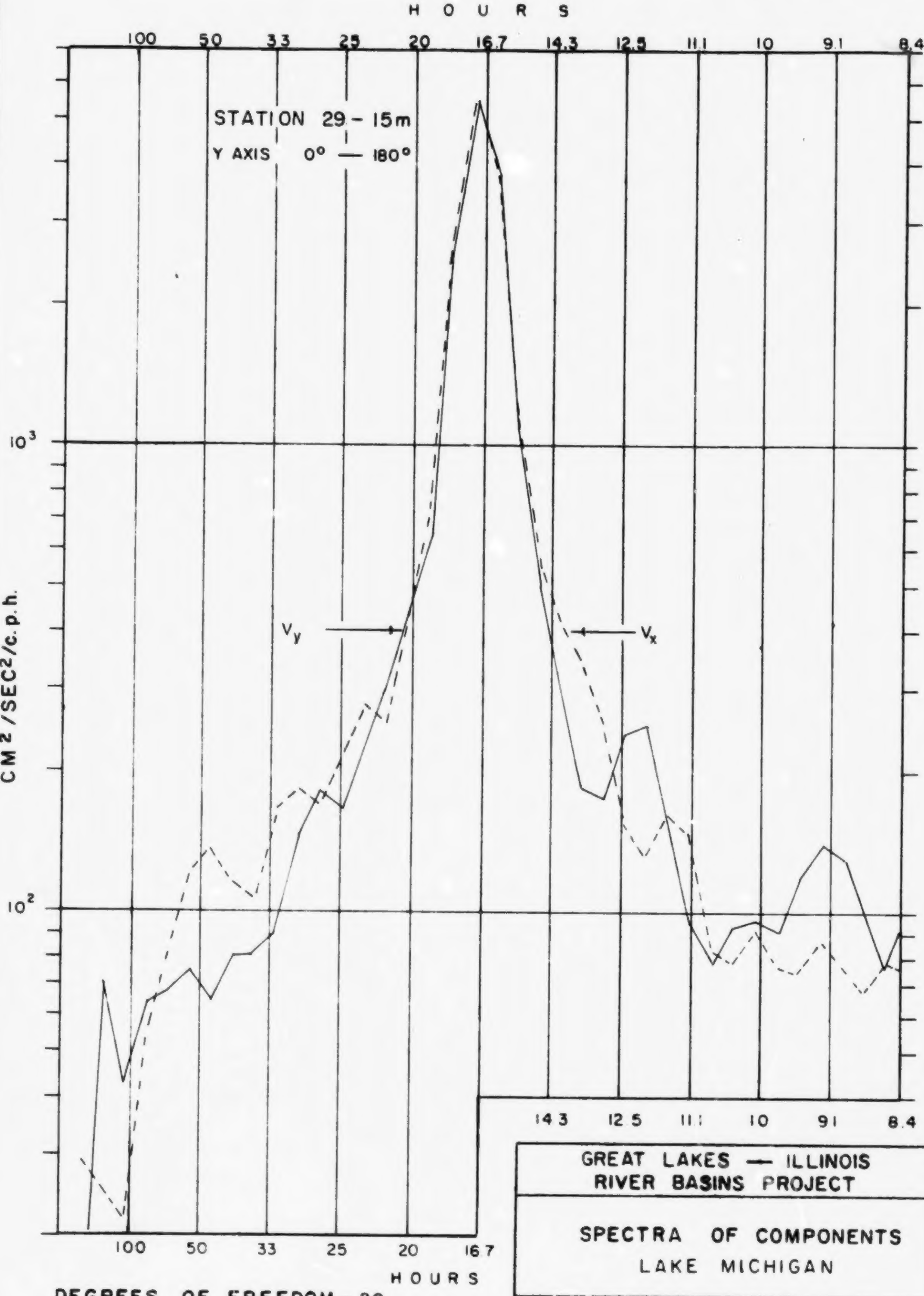
DEGREES OF FREEDOM - 20
DATE - 5/10/4-7/5/4
NO. OF OBSERVATIONS - 4029

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-27



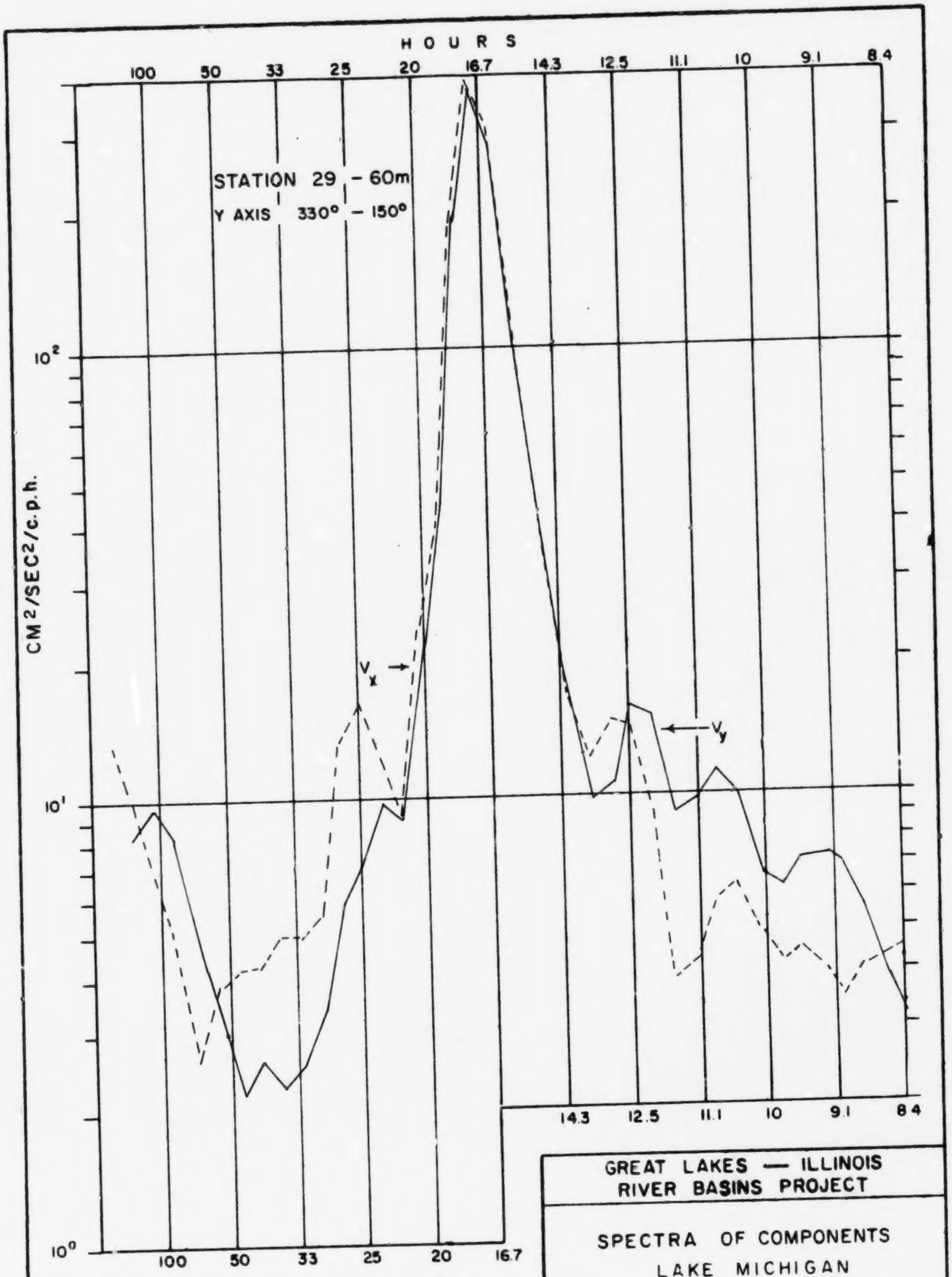
DEGREES OF FREEDOM - 20
DATE - 8/20/3 - 10/28/3
NO. OF OBSERVATIONS - 4924

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-28



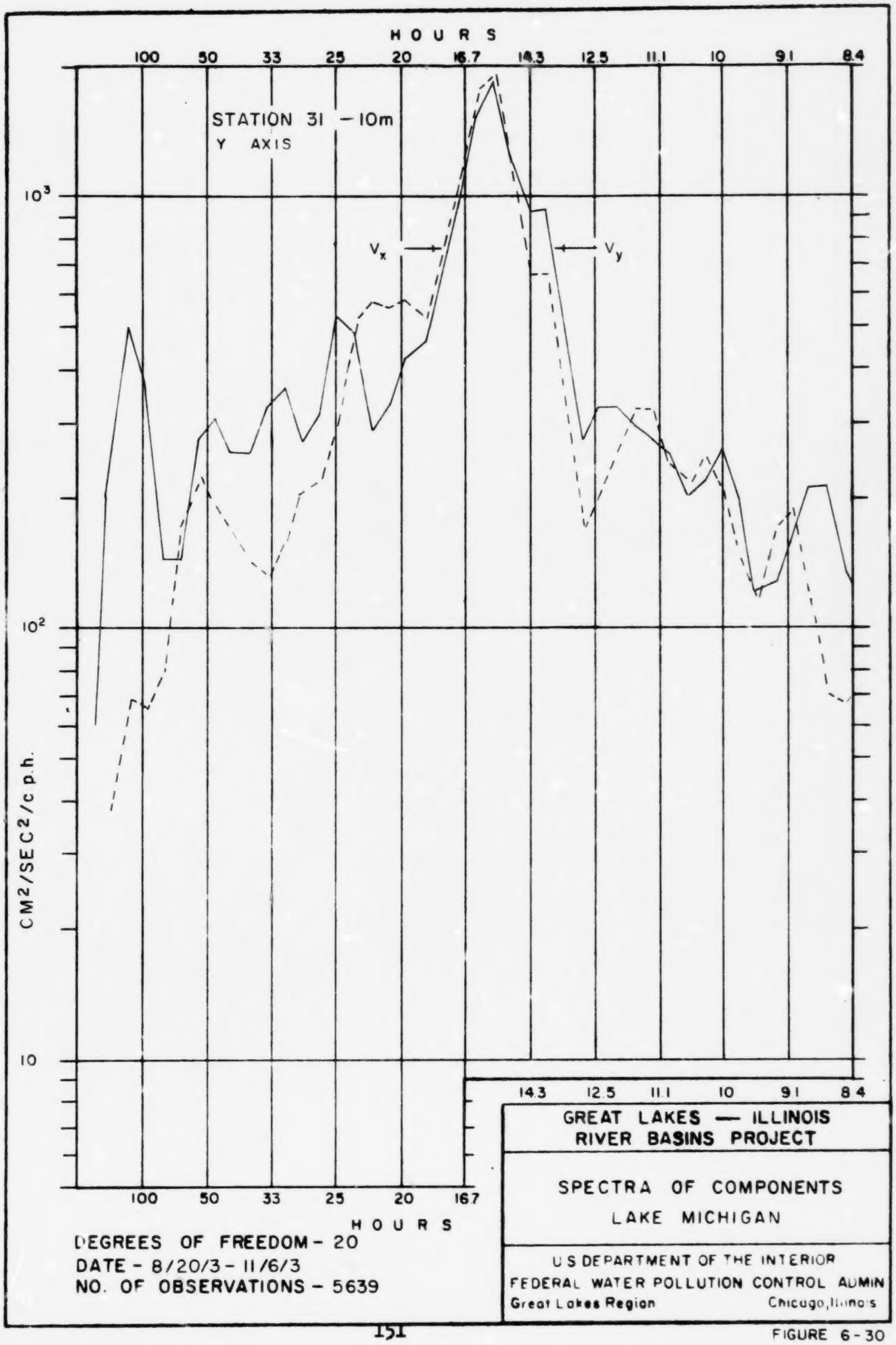
DEGREES OF FREEDOM- 20
DATE — 8/20/3-10/28/3
NO. OF OBSERVATIONS - 4950

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-29



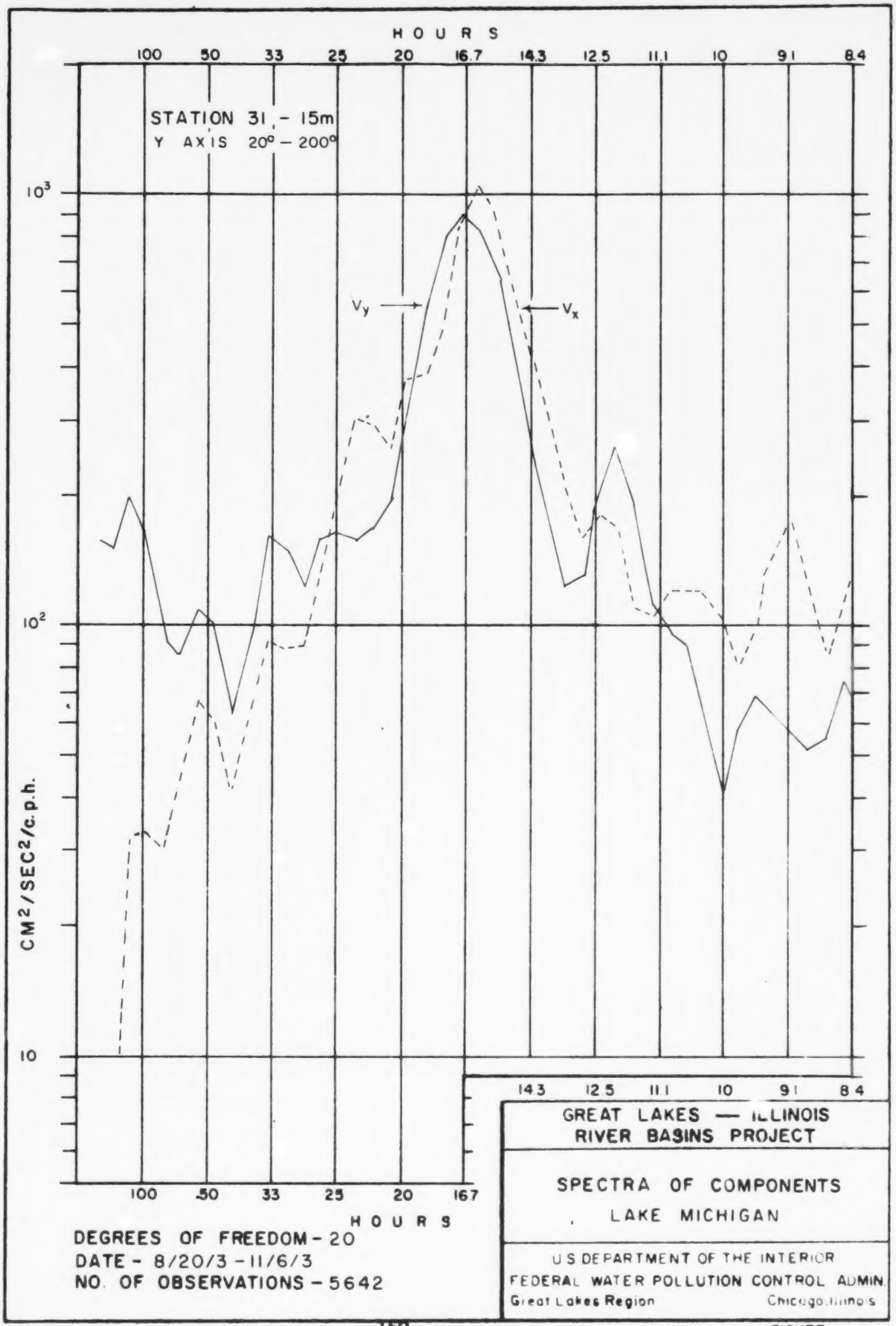
DEGREES OF FREEDOM - 20
DATE - 8/20/3 - 11/6/3
NO. OF OBSERVATIONS - 5639

GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-30



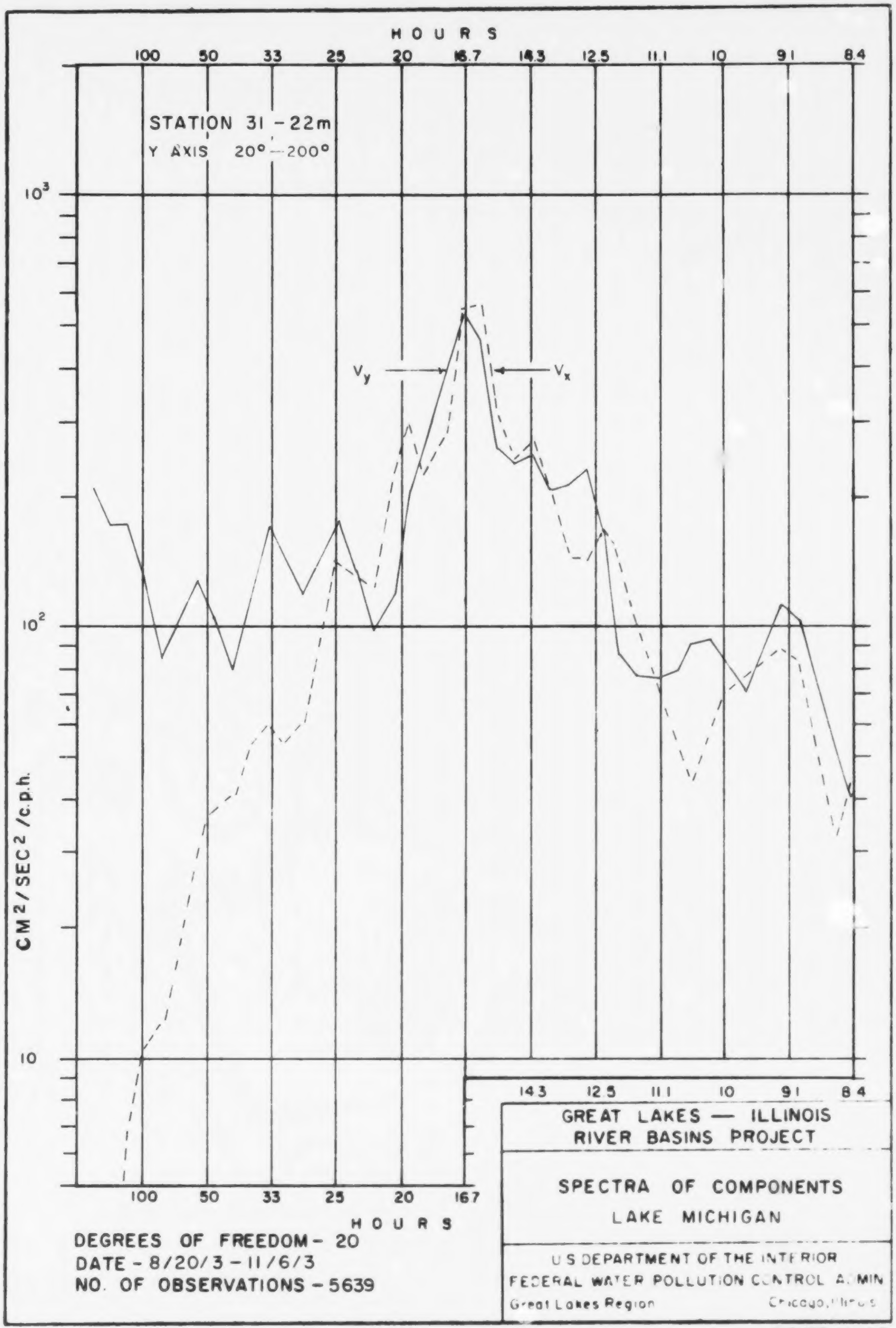
DEGREES OF FREEDOM - 20
DATE - 8/20/3 - 11/6/3
NO. OF OBSERVATIONS - 5642

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-31



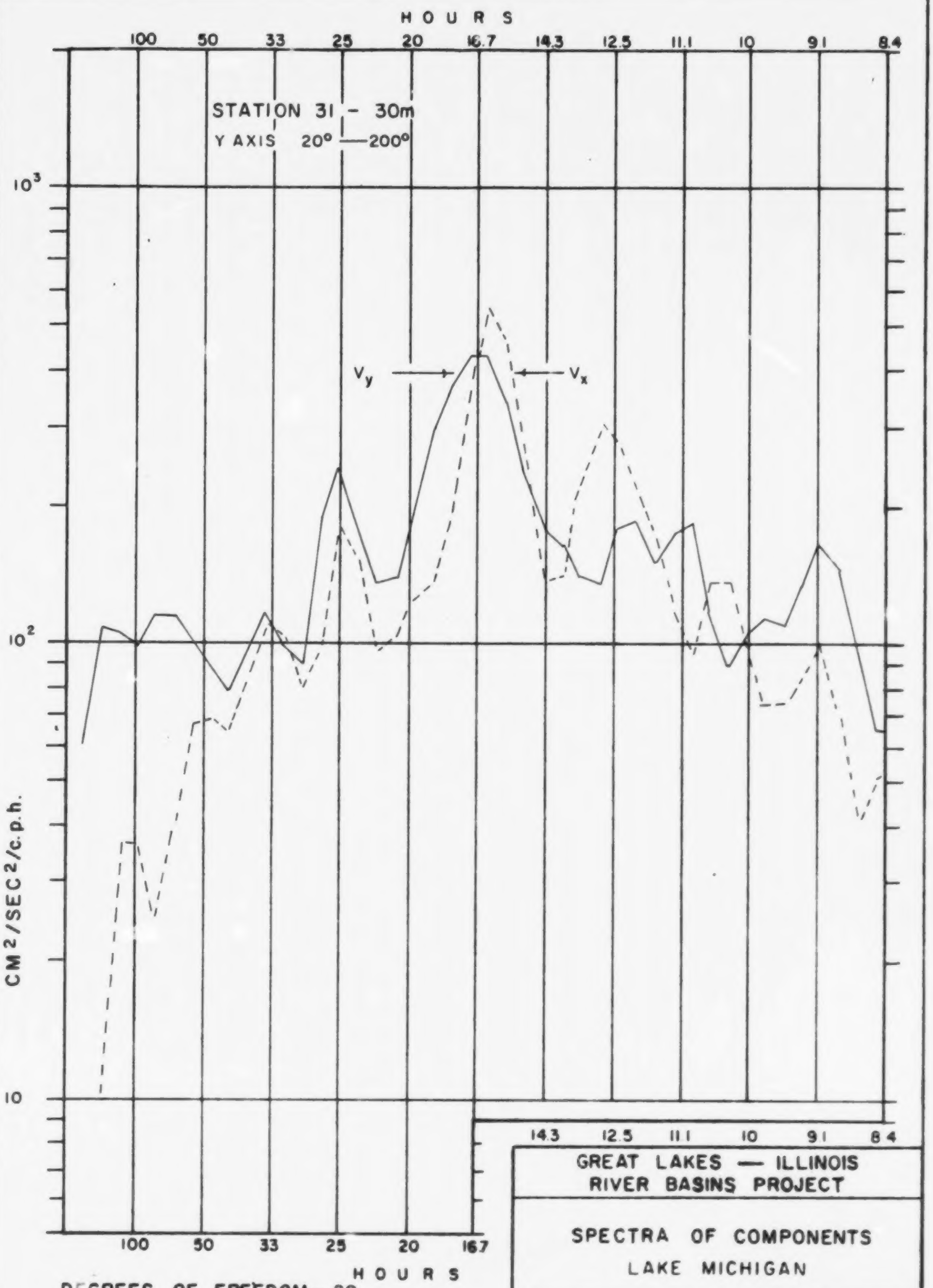
DEGREES OF FREEDOM - 20
DATE - 8/20/3 - 11/6/3
NO. OF OBSERVATIONS - 5639

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-32



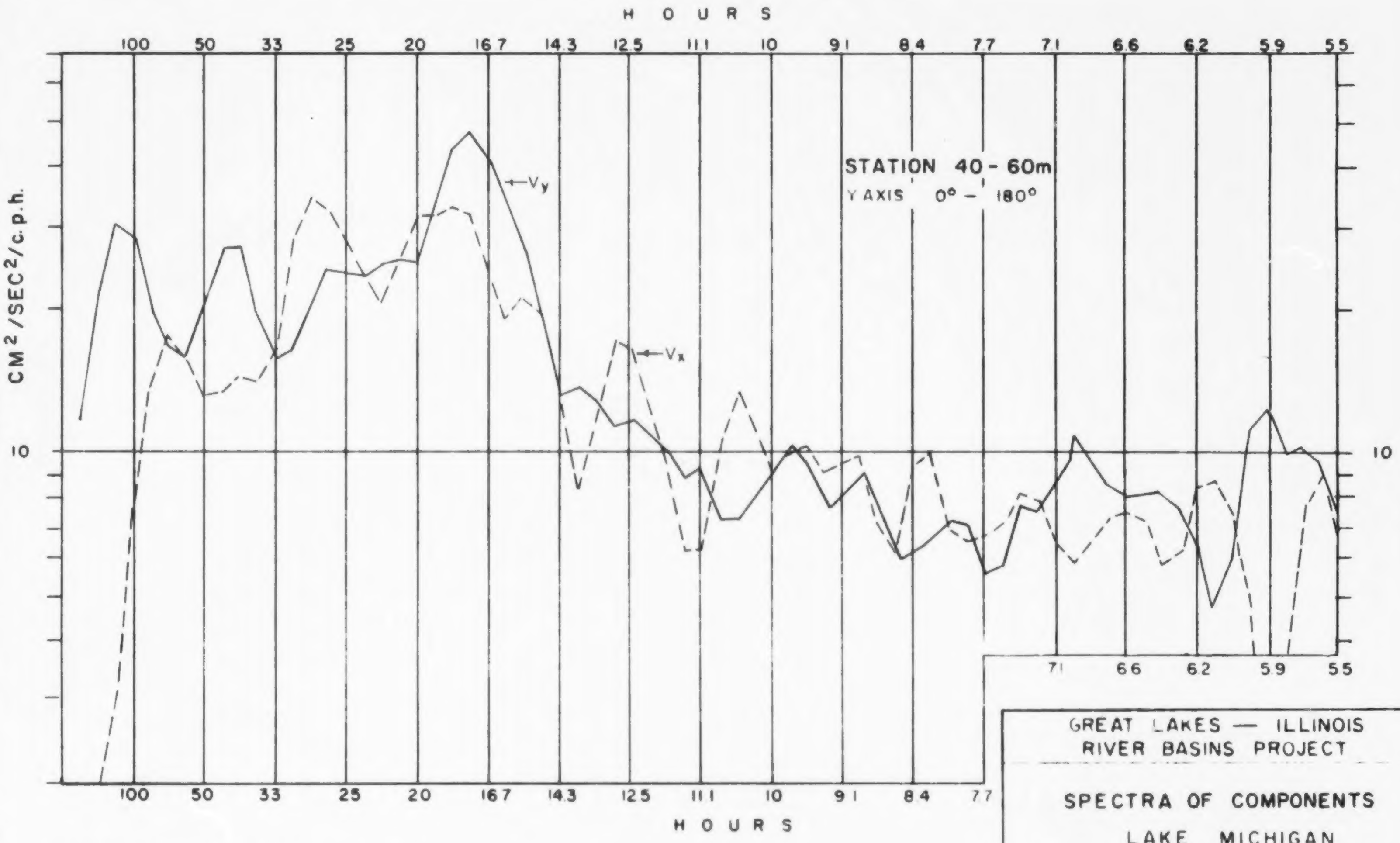
DEGREES OF FREEDOM - 20
DATE - 8/20/3 - 11/6/3
NO. OF OBSERVATIONS - 5580

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-33



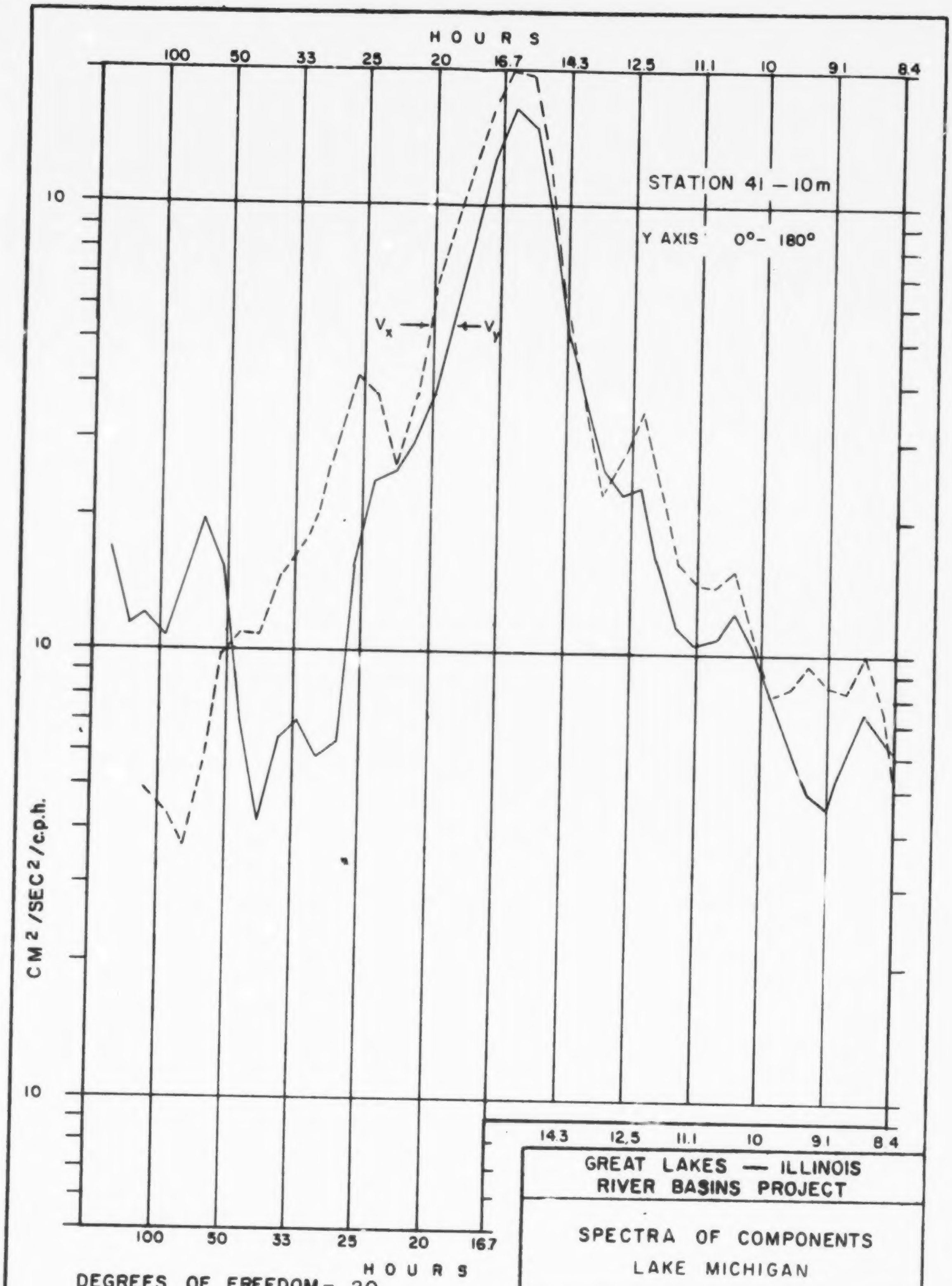
DEGREES OF FREEDOM - 28
DATE - 12/3/3 — 3/31/4
NO. OF OBSERVATIONS - 5658

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region [illegible]

FIGURE 6-34



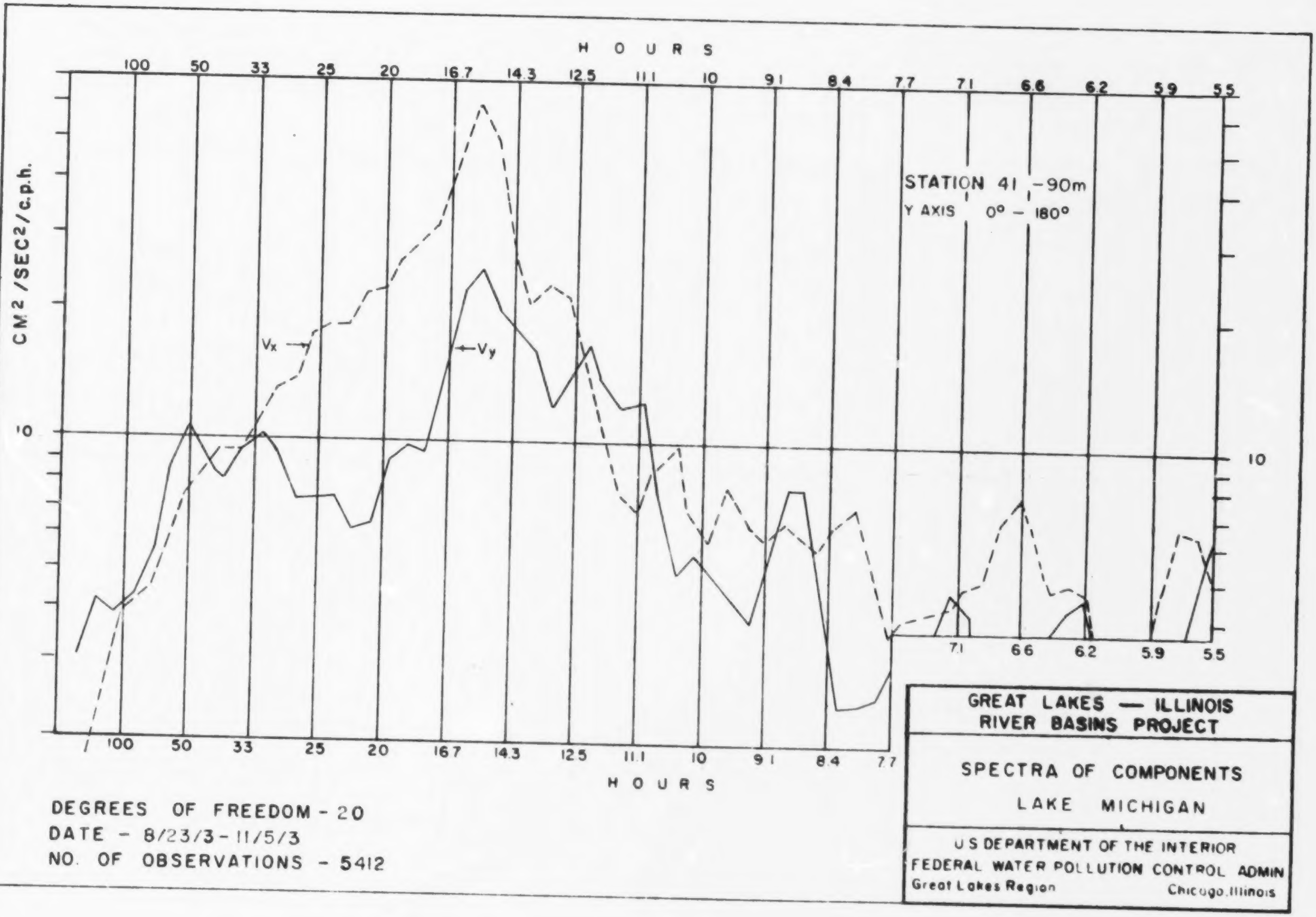
DEGREES OF FREEDOM - 20
DATE - 8/22/63 - 11/5/63
NO. OF OBSERVATIONS - 5412

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-35



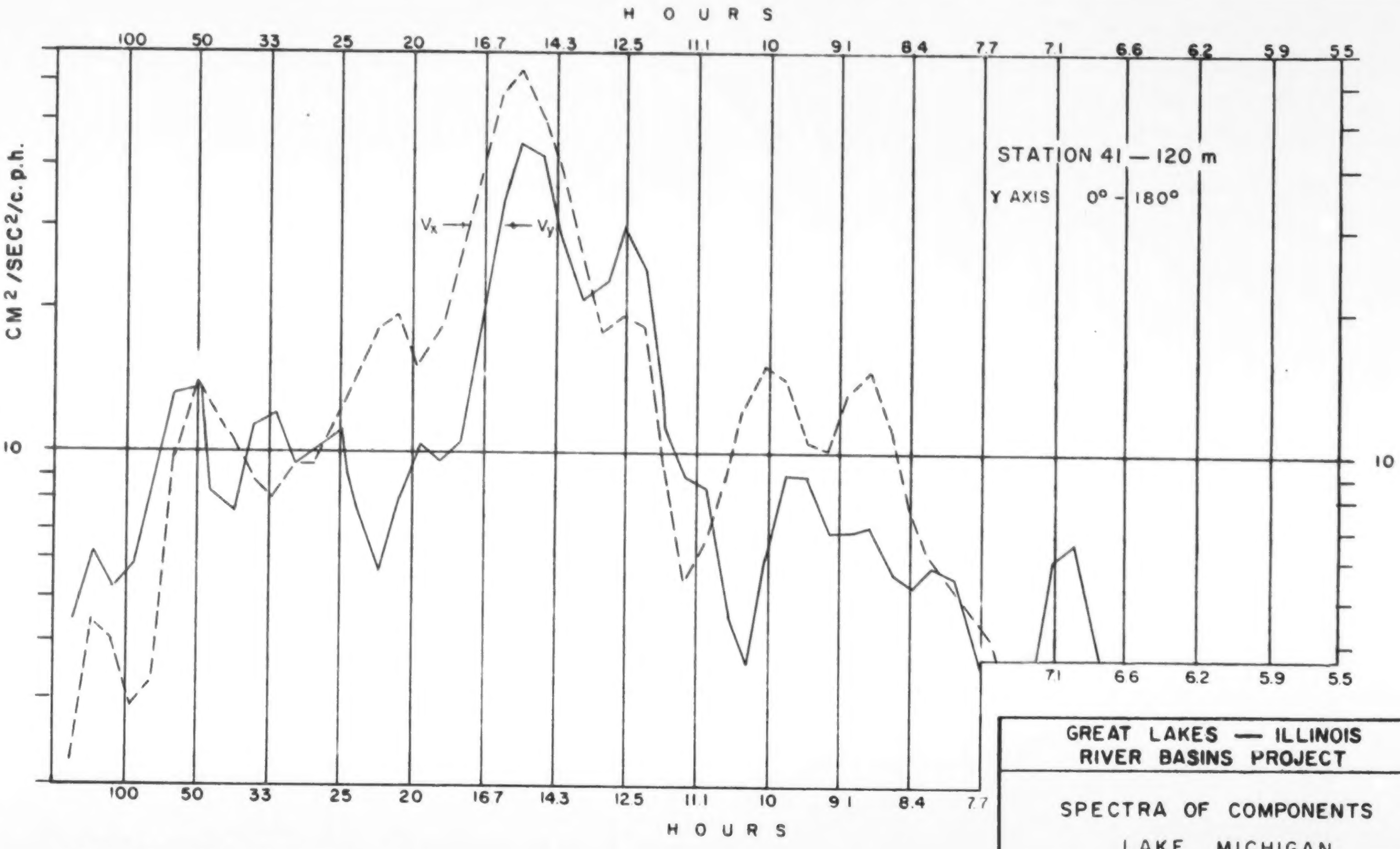
DEGREES OF FREEDOM - 20
DATE - 8/23/3 - 11/5/3
NO. OF OBSERVATIONS - 5412

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-36



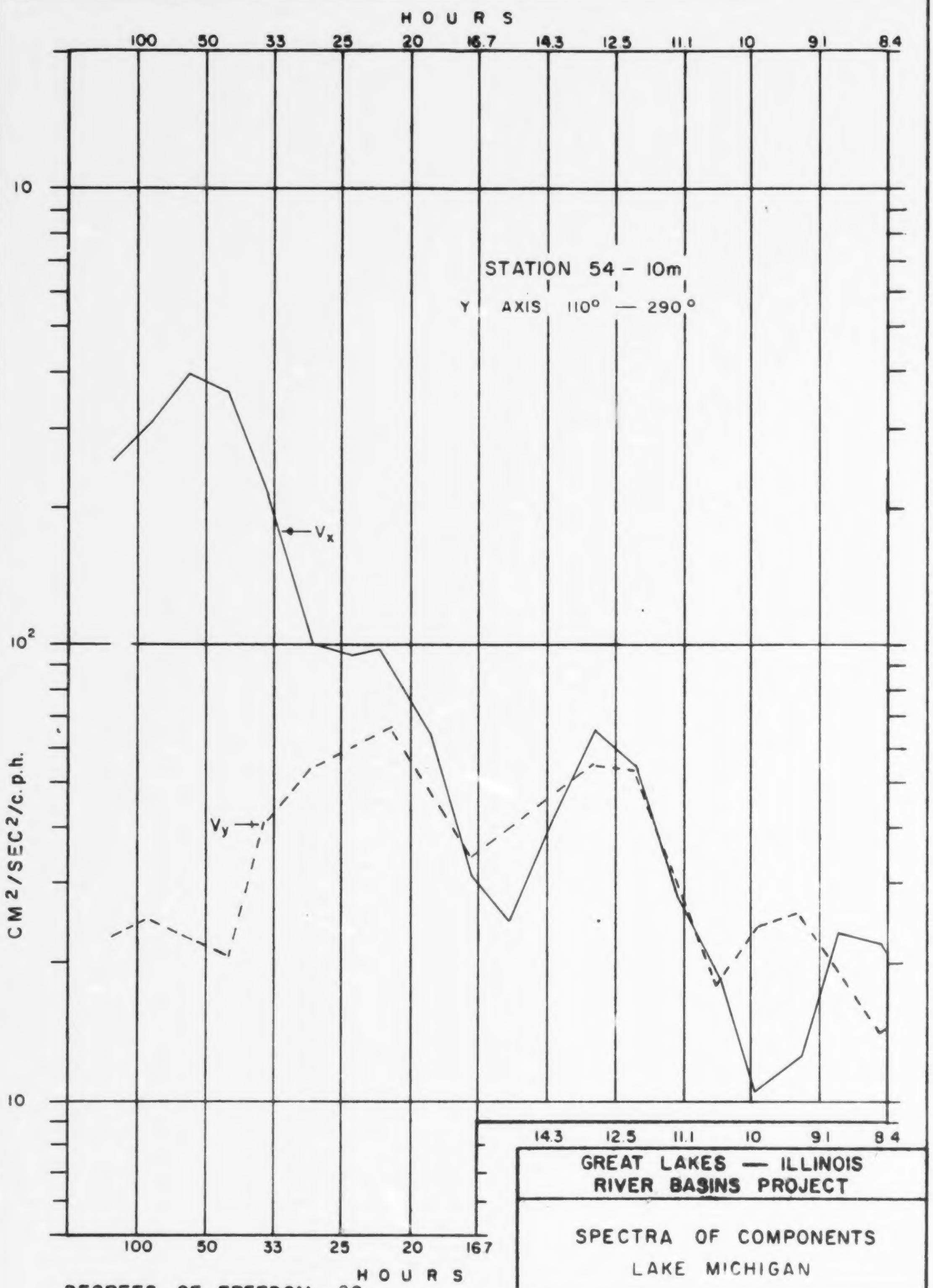
DEGREES OF FREEDOM - 20
DATE - 8/23/63 - 11/5/63
NO. OF OBSERVATIONS - 5332

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-37



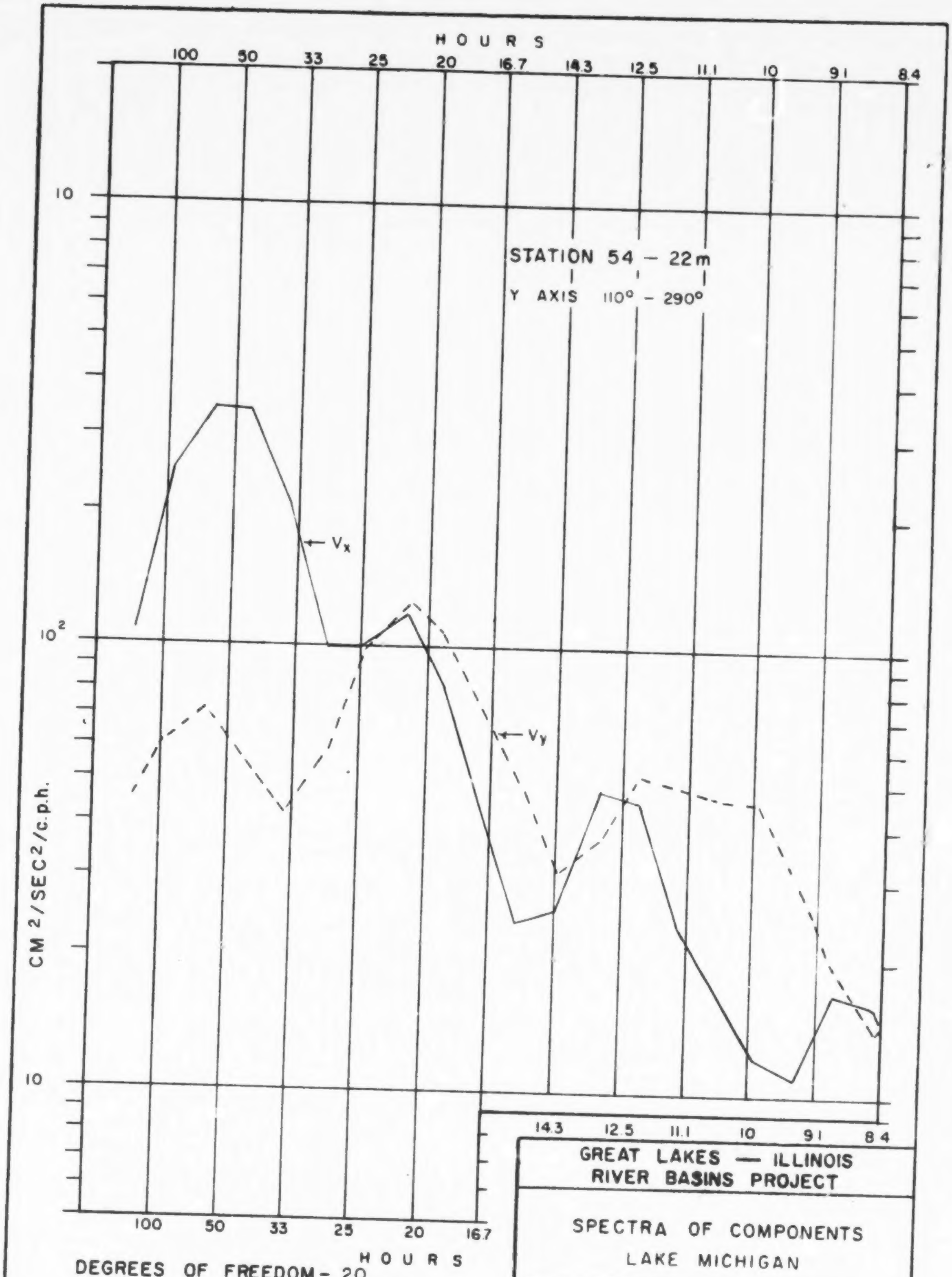
DEGREES OF FREEDOM - 20
DATE - 9/24/3 - 10/30/3
NO. OF OBSERVATIONS - 422 Sub-sample

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-38



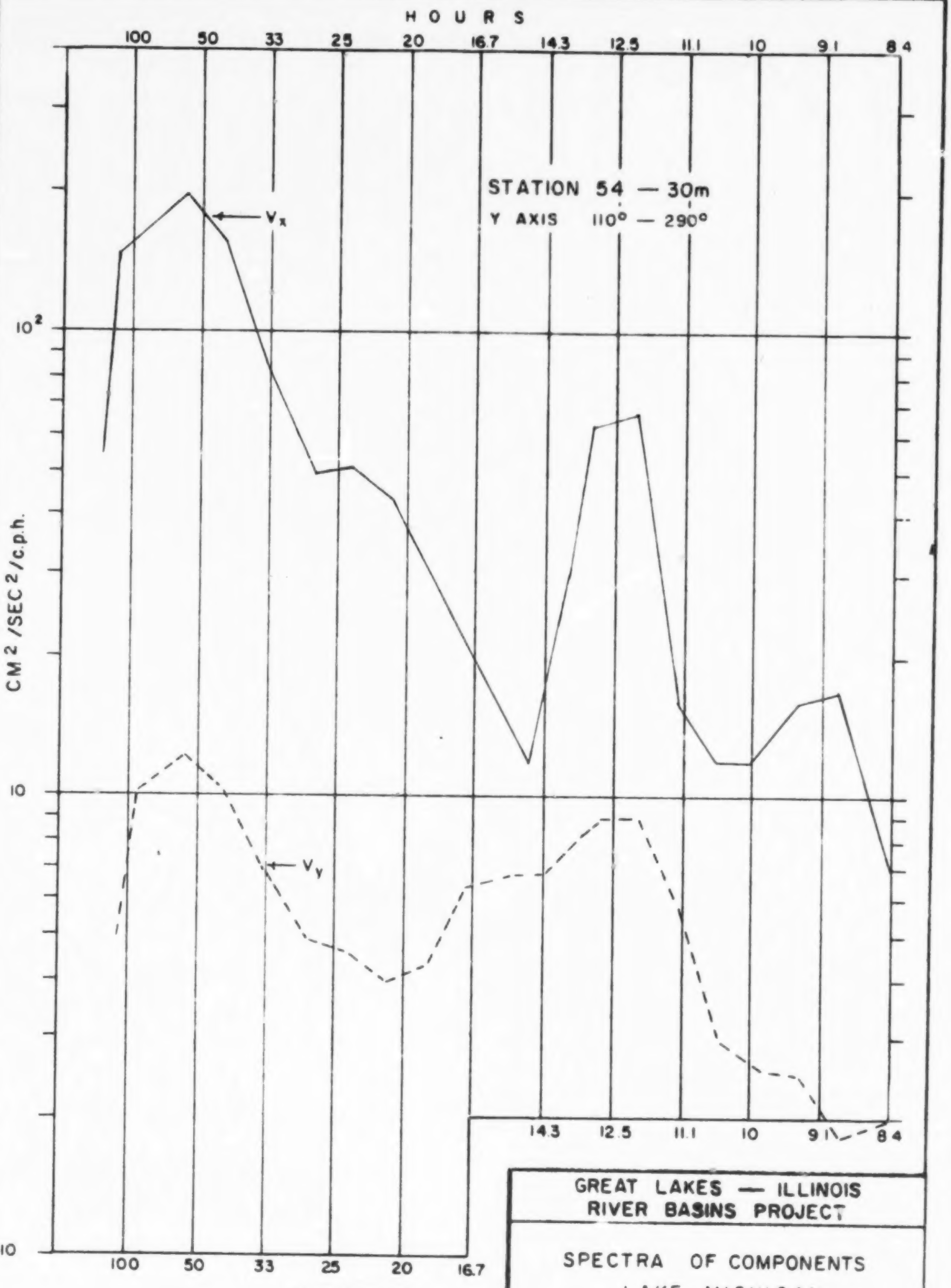
DEGREES OF FREEDOM - 20
DATE - 9/24/3 — 10/30/3
NO. OF OBSERVATIONS - 375 Sub-sample

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-39



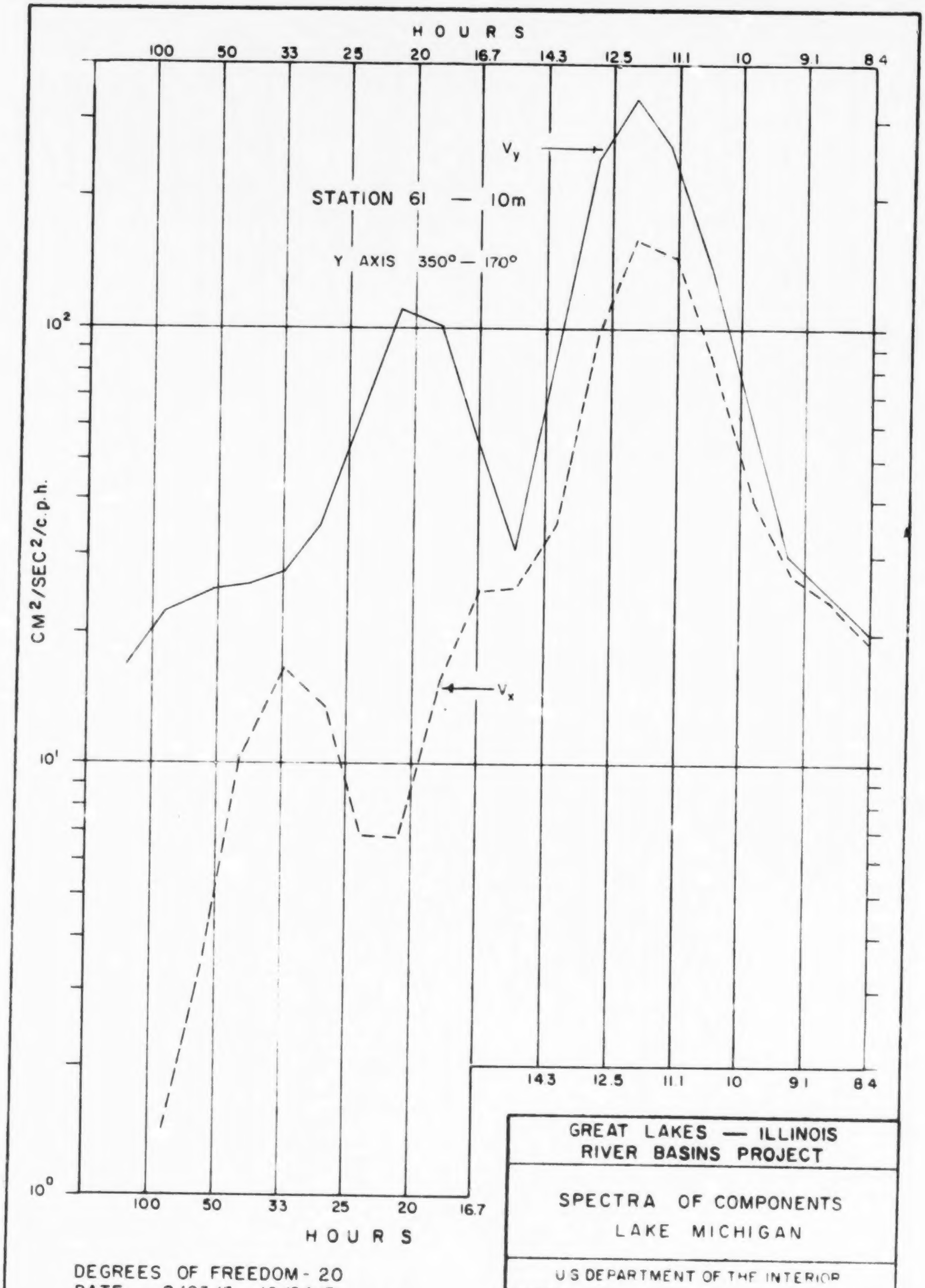
DEGREES OF FREEDOM - 20
DATE — 9/24/3 - 10/30/3
NO OF OBSERVATIONS - 426 Sub-sample

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-40



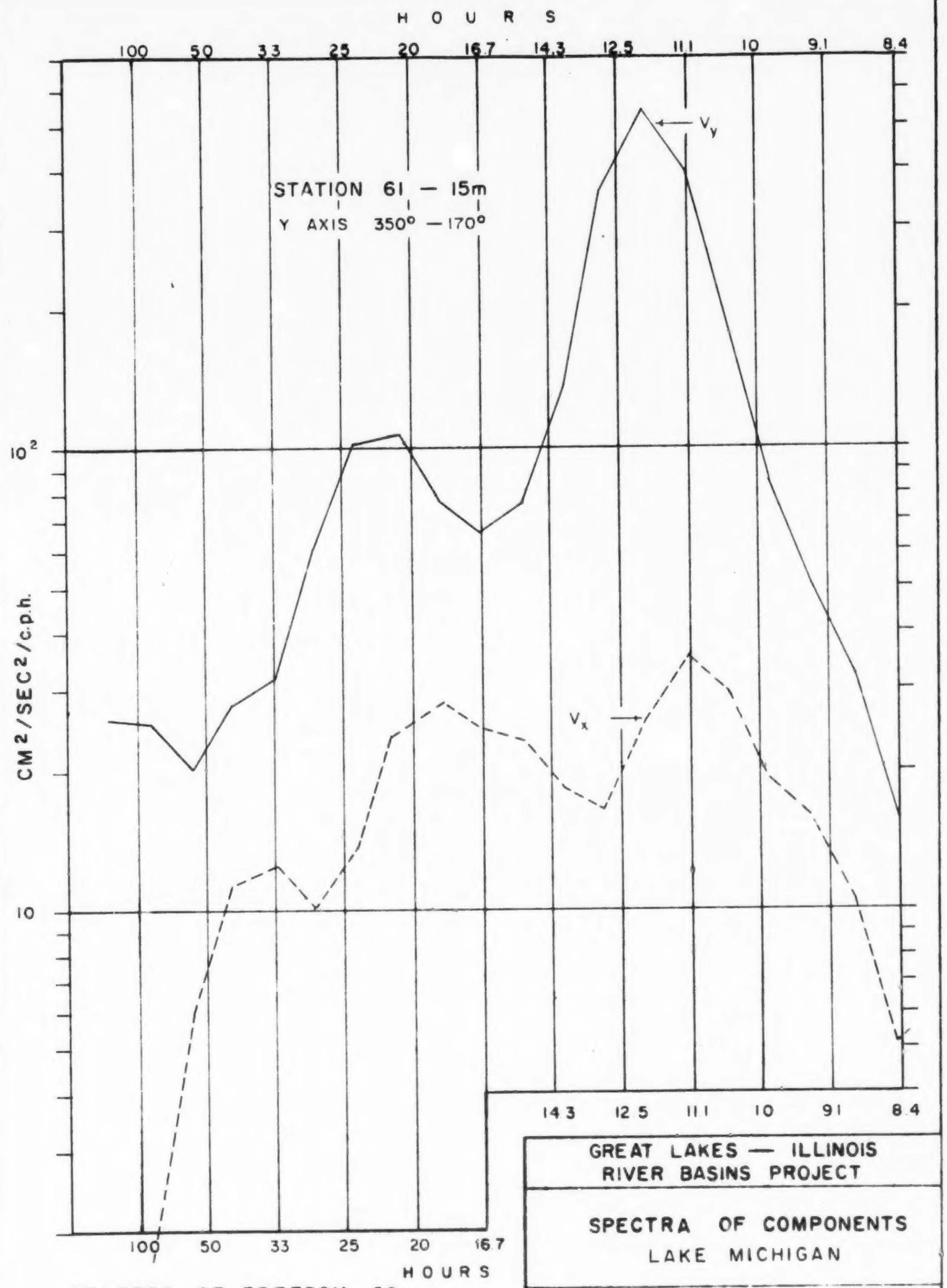
DEGREES OF FREEDOM - 20
DATE — 9/23/3 – 10/24/3
NO OF OBSERVATIONS - 2604

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-41



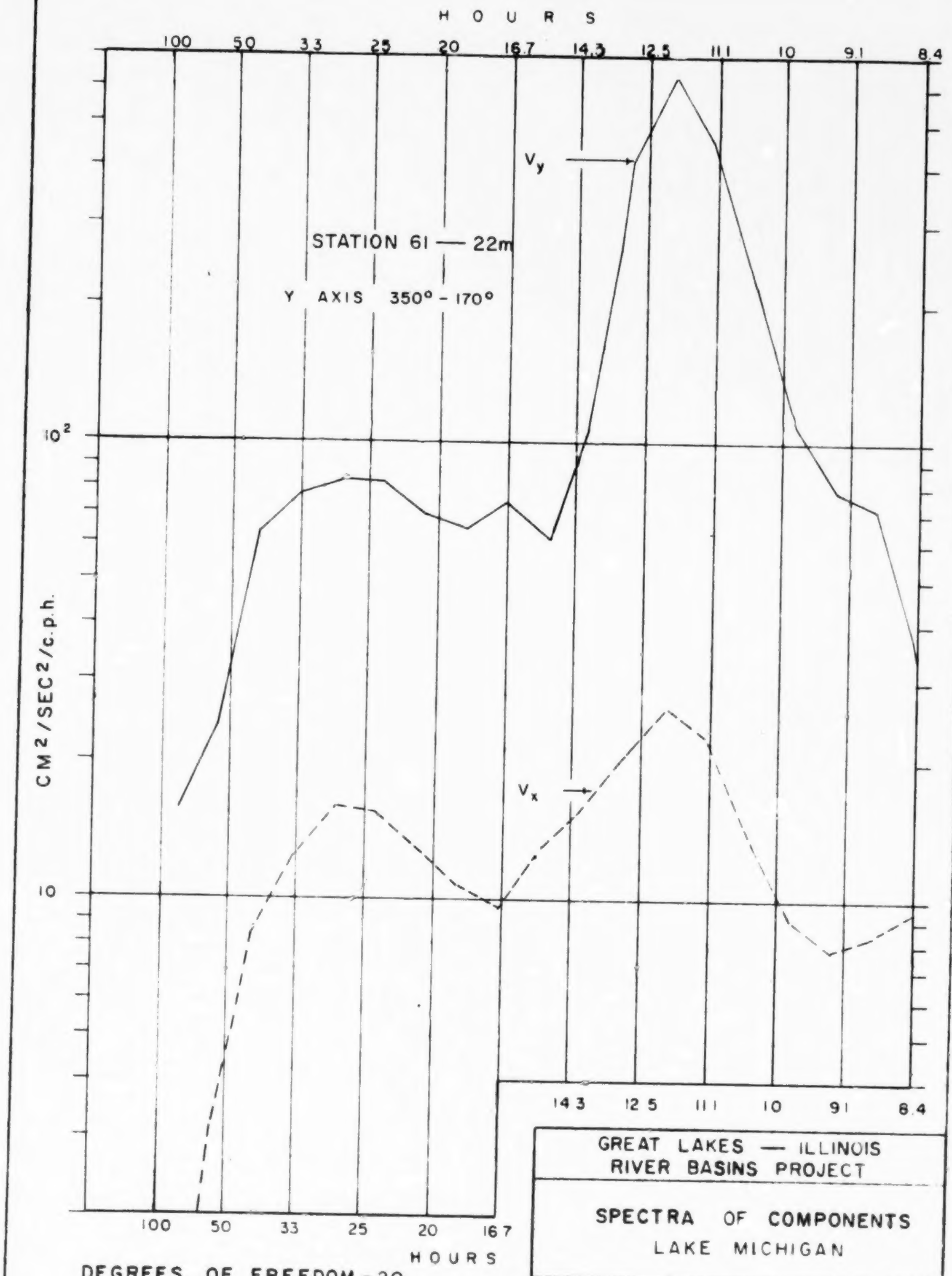
DEGREES OF FREEDOM - 20
DATE - 9/23/3 - 10/24/3
NO. OF OBSERVATIONS - 2604

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 6-42



DEGREES OF FREEDOM - 20
DATE - 9/23/3 - 10/24/3
NO. OF OBSERVATIONS - 2604

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region [illegible]

FIGURE 6-43

TABLE 6-7

LAKE MICHIGAN CURRENT SPECTRA DATA

STATION	DEPTH (M)	FILM NUMBER 200-	DATES OF SPECTRAL RECORDS START	END	AXIS ORIENTATION (Y AXIS)	NEARSHORE STATION	OFFSHORE STATION	SUMMER DATA	WINTER DATA	SPEED SPECTRA	VELOCITY COMPONENT SPECTRA
03	015	005	01/28/63	03/22/63	325-145	x			x	x	x
04	010	000	01/04/63	03/22/63	0-180		x		x	x	x
	015	001	12/21/62	03/22/63	345-165		x		x	x	x
	022	002	12/24/62	03/22/63	305-125		x		x	x	x
05	015	197	11/25/63	04/13/64	25-205		x		x	x	x
	030	199	11/25/63	04/13/64	26-206		x		x	x	x
07	010	120	07/31/63	11/10/63	0-180	x		x		x	x
	015	121	07/31/63	11/10/63	0-180	x		x		x	x
08	010	065	07/30/63	10/16/63	0-180		x	x		x	x
	015	063	07/30/63	10/16/63	0-180		x	x		x	x
	022	056	07/30/63	10/16/63	0-180		x	x		x	x
	030	057	07/30/63	10/16/63			x	x		x	
	060	049	07/30/63	10/16/63			x	x		x	
09	015	062	08/18/63	10/17/63	0-180		x	x		x	x
	030	053	08/18/63	10/17/63	0-180		x	x		x	x
	090	054	08/18/63	10/17/63	0-180		x	x		x	x
10	015	050	08/16/63	10/17/63	0-180		x	x		x	x
	022	060	08/16/63	10/17/63	0-180		x	x		x	x
	030	061	08/16/63	10/17/63	0-180		x	x		x	x
	060	043	08/16/63	10/17/63	0-180		x	x		x	x
	022	231	11/25/63	04/15/64	26-206		x		x		x
	010	316	05/11/64	07/05/64	0-180		x	x		x	x
	015	317	05/11/64	07/05/64	0-180		x	x		x	x
13	010	236	11/19/63	04/11/64			x		x	x	
	015	237	11/19/63	04/11/64			x		x	x	
	022	238	11/19/63	04/11/64			x		x	x	
	030	239	11/19/63	04/11/64			x		x	x	
	090	241	11/19/63	04/11/64			x		x	x	
	010	350	04/10/64	07/08/64	0-180		x	x		x	x
	030	353	04/10/64	07/08/64	0-180		x	x		x	x
	060	354	04/10/64	07/08/64	0-180		x	x		x	x
	090	355	04/10/64	07/08/64			x	x		x	

TABLE 6-7 (Continued)

LAKE MICHIGAN CURRENT SPECTRA DATA

STATION	DEPTH (M)	FILM NUMBER 200-	DATES OF SPECTRAL RECORDS START	END	AXIS ORIENTATION (Y AXIS)	NEARSHORE STATION	OFFSHORE STATION	SUMMER DATA	WINTER DATA	SPEED SPECTRA	VELOCITY COMPONENT SPECTRA
17	010	356	04/02/64	07/09/64	0-180	x		x		x	x
	015	357	04/02/64	07/09/64							
18	010	009	12/02/63	04/20/63	26-206		x		x	x	x
20	015	015	11/30/62	04/17/63			x		x	x	x
	100	019	11/30/62	04/17/63	325-145		x		x	x	x
	022	137	07/12/63	11/07/63	0-180		x	x		x	x
	060	139	07/12/63	11/07/63			x	x		x	
	090	140	07/12/63	11/07/63	0-180		x	x		x	x
	010	247	12/07/63	04/16/64	345-165		x		x	x	x
	060	251	12/07/63	04/16/64			x		x	x	
	010	306	05/10/64	07/05/64			x	x		x	
	015	307	05/10/64	07/05/64	0-180		x	x		x	x
	022	308	05/10/64	07/05/64			x	x		x	
	090	311	05/10/64	07/05/64	0-180		x	x		x	x
27	015	359	04/23/64	07/10/64		x		x		x	
	022	360	04/23/64	07/10/64	45-225	x		x		x	x
29	010	107	08/20/63	10/28/63			x	x		x	
	015	108	08/20/63	10/28/63	0-180		x	x		x	x
	022	109	08/20/63	10/28/63			x	x		x	
	060	111	08/20/63	10/28/63	330-150		x	x		x	x
30	015	254	12/05/63	04/20/64			x		x	x	
	030	256	12/05/63	04/20/64	65-245		x		x	x	x
	060	257	12/05/63	04/20/64	65-245		x		x	x	x
	090	258	12/05/63	04/20/64			x		x	x	
	120	259	12/05/63	04/20/64	65-245		x		x	x	x
	150	260	12/05/63	04/20/64			x		x	x	
31	010	142	08/20/63	11/06/63	20-200	x		x		x	x
	015	143	08/20/63	11/06/63	20-200	x		x		x	x
	022	144	08/20/63	11/06/63	20-200	x		x		x	x
	030	145	08/20/63	11/06/63	20-200	x		x		x	x

TABLE 6-7 (Continued)

LAKE MICHIGAN CURRENT SPECTRA DATA

STATION	DEPTH (M)	FILM NUMBER 200-	DATES OF SPECTRAL RECORDS START	DATES OF SPECTRAL RECORDS END	AXIS ORIENTATION (Y AXIS)	NEARSHORE STATION	OFFSHORE STATION	SUMMER DATA	WINTER DATA	SPEED SPECTRA	VELOCITY COMPONENT SPECTRA
37	010	261	12/02/64	04/21/64	25-205	x			x	x	x
	030	264	12/02/64	04/21/64	25-205	x			x	x	x
	022	295	04/20/64	07/03/64	25-205	x		x		x	x
	030	296	04/20/64	07/03/64		x		x		x	
	060	297	04/20/64	07/03/64	25-205	x		x		x	x
38	030	218	12/02/63	05/04/64			x		x	x	
	120	221	12/02/63	05/04/64	45-225		x		x	x	x
39	090	027	12/04/62	03/21/63			x		x	x	
	150	029	12/04/62	03/21/63			x		x	x	
	210	031	12/04/62	03/21/63			x		x	x	
	022	150	08/22/63	11/06/63	0-180		x	x		x	x
	030	151	08/22/63	11/06/63			x	x		x	
	120	154	08/22/63	11/06/63	0-180		x	x		x	x
	180	156	08/22/63	11/06/63			x	x		x	
40	010	266	01/22/64	04/19/64	26-206		x		x	x	x
	060	270	01/22/64	04/19/64	0-180		x		x	x	x
	120	272	01/22/64	04/19/64			x		x	x	
41	010	160	08/22/63	11/05/63	0-180	x		x		x	x
	015	161	08/22/63	11/05/63		x		x		x	
	090	165	08/22/63	11/05/63	0-180	x		x		x	x
	120	166	08/22/63	11/05/63	0-180	x		x		x	x
54	010	077	09/24/63	10/30/63	110-290	x				x	x
	022	079	09/24/63	10/30/63	110-290	x				x	x
	030	080	09/24/63	10/30/63	110-290	x				x	x
61	010	072	09/23/63	10/29/63	350-170		x				x
	015	073	09/23/63	10/29/63	350-170		x				x
	022	074	09/23/63	10/29/63	350-170		x				x

Station 4 is located in the southern basin of Lake Michigan. It is an offshore station and the data were collected between January 4, 1963 and March 22, 1963. The recorders were located at three depths; 10, 15, and 22 m. The principal peak located in the 10-m speed spectrum was at 91 hours (hr) and in the 15- and 22-m speed spectra at 100 hr. Another peak in the 15-m spectrum is at 8.9 hr. The 91- to 100-hr period is probably due to long wave pressure systems, such as Rossby waves. Apparently there is some forcing by meteorological disturbances which tend to come at intervals, on the average, of about 4 or 5 days; and this is confirmed in the spectra of wind data. The 8.9-hr period is Lake Michigan's first mode. The Vx spectra were primarily noise and no statistically reliable peaks were observed. The Vy spectra showed important peaks at 91 hr in the 10-m record, 8.6 and 111 hr at 15 m, and 100 hr at 22 m.

Station 5 is an offshore station in the southern basin of Lake Michigan near the southeast shore. The data were gathered for two depths, 15 and 22 m, during November 25, 1963 to April 13, 1964. The speed spectra contained no reliable peaks. The velocity components showed tendencies of energy to peak around 10 and 20 hr.

Station 7 is an inshore station near the middle of the southern basin. The data were gathered for two depths, 10 and 15 m, during July 31, 1963 to November 10, 1963. The speed spectra have several peaks which are reliable. At 10 m there is a peak at 45.5 hr while at 15 m there is a broad peak between 33 and 50 hr and also one at 16.7 hr. The energy was generally in the high frequency oscillations for the speed spectra. In the Vx spectra at the 10-m depth, there are peaks at 9.1, 18.2, and 50 hr, while at 15 m the peaks are at 18.2, 33, and a broad peak between 8.8 to 9.5 hr. The Vy spectrum has a broad peak between 50 and 100 hr and another peak at 18.2 hr in the 10-m record. At 15 m there is a peak at 18.2 and 55 hr.

Station 8 is an offshore station in the southern basin and is west of the center of the Lake. The date of these observations at depths of 10, 15, 22, 30 and 60 m, was between July 20, 1963 and October 16, 1963. The speed spectra showed a gigantic inertial frequency peak at 17.2 hr in the 22-m record, 17.5 hr at 10, 15, and 60 m; and an indication of peaking around 17 hr at 30 m. The Vx spectra have a gigantic peak at 17.4 hr at 10, 15, and 22 m. The peaks in the Vy spectra have identical period estimates as the Vx spectra but are slightly smaller in energy magnitude at corresponding depths. The inertial period at this location is 17.8 hr.

Station 9 is located in the southern basin and approximately in the center of the Lake, at this latitude. The data for the spectra were collected between August 18, 1963 and October 17, 1963. Speed spectra for depths 15, 22, 30, 60, and 90 m were calculated from these data. The velocity component spectra were computed for 15, 30, and 90 m. For the speed spectrum, the principal peak is near the inertial period with each depth having its peak at a different time: 15 m (17.9 hr), 22 m (19.6 hr), 30 m (16.4 hr), 60 m (15.6 hr), 90 m (14.9 hr). The 15-m record also has a significant peak at 8.3 hr. The Vx spectrum gives estimates with a 0.4-hr spread in the location of the inertial period from 17.5 hr for 30 m to 17.9 hr for 15 and 90 m. The 15-m spectrum has another peak at 8.6 hr and the 30-m spectrum has a questionable peak at 8.9 hr. The Vy spectra show the same period estimates as do the Vx spectra, Figures 6-17, 6-18, and 6-19.

Station 10 is an offshore station in the southern basin east of the center of the Lake. The duration of the first data collection was from August 16, 1963 to October 17, 1963. The data were collected at depths of 15, 22, 30, and 60 m. At 15 m, two significant peaks are computed in the speed spectra, one at 8.5 hr and the other at 17.4 hr. At 22 m a peak is found at 17.2 hr and an indication of a significant peak at 8.8 hr. The 30-m spectrum is noise with more energy evident in the low frequency. The 60-m spectrum has a peak at 17.2 hr. The Vx spectra revealed a peak near the inertial period of around 17.4 hr at 15 m, 17.2 hr at 22, 30, and 60 m. Spectral peaks of the first mode of Lake Michigan appeared at 8.8 hr in the 15- and 22-m records, 8.6 to 8.8 hr at 60 m. For the Vy spectra two peaks are evident at the following times and depths: 8.5 and 17.5 hr at 15 m, 8.8 and 17.2 hr at 22 m, 8.7 and 17.2 hr at 30 m, 8.6 and 17.1 hr at 60 m.

The second set of data was a winter record between November 25, 1963 and April 15, 1964 at 22 m. Only velocity components are available. The Vx spectra are mostly noise. The Vy spectra have two significant peaks; one at 23.6 and the other at 18.2 hr.

The third set of data was recorded between May 11, 1964 and July 5, 1964 at 10, 15, and 22 m. The speed spectra show a peaking of energy around 16 and 24 hr. The Vx spectrum has two peaks, one at 9.1 and another at 17.2 hr, in the 10-m record; and one peak at 18.2 hr in the 15-m record. The Vy spectrum has the same features excepting the peak at 9.1 hr is broadened into a square peak between 8.6 and 9 hr, Figures 6-20 and 6-21.

Station 13 is located in the southern basin of Lake Michigan, west of the center of the Lake. Winter speed data for depths of 10, 15, 22, 30, and 90 m, during November 19, 1963 to April 11, 1964 show primarily a random response due in part to a high number of zero speed readings. The summer data were recorded between April 10, 1964 and July 8, 1964 at 10, 30, 60, and 90 m. The speed spectra show a peaking of energy around the inertial period but the Vx and Vy spectra show a very strong peaking at the inertial oscillation at 17.4 hr for depths of 10, 30, and 60 m. There is evidence of the first free oscillation of Lake Michigan in the Vy spectra between 9 and 9.5 hr, Figure 6-22 to 6-24.

Station 17 is located in the northern part of Lake Michigan's southern basin near the western shore. The data were collected during the summer of 1964 from April 2 to July 9 at depths of 10 and 15 m. The principal peak in the 10-m speed spectrum is that near the inertial oscillation at 15.4 hr. There were no statistically significant peaks in the speed spectrum at the 15-m depth. In the 10-m record the Vx and Vy spectra show one significant peak around 16 hr, Figure 6-25.

Station 18 is an offshore station located near the northwestern end of the southern basin. The data were collected between December 2, 1962 and April 20, 1963 at the 10-m depth. The speed spectrum has a peak near the inertial period at 18.8 hr. The velocity component spectra have the same peak at 18.2 hr; however, due to an abnormally high number of zero speeds, the period estimates are not too reliable.

Station 20 is an offshore station located near the northeast end of the southern basin. There are four sets of data starting November 1962 and ending July 1964. The first record is from November 30, 1962 to April 17, 1963. at 15 and 100 m. The 15-m depth shows an inertial peak at 18.1 hr but also contained an unidentifiable peak at 33.3 hr which might be due to spurious data. The 100-m speed spectrum has an inertial peak at 18.5 hr and the Vx spectrum's inertial peak is at 17.8 hr. The Vy spectrum is mostly noise. The second record is from July 12, 1963 and November 7, 1963 at 22, 60, and 90 m. An inertial oscillation shows a peak at 16.0 hr at 22 m, 17.4 hr at 60 and 90 m in the speed spectra. The Vx spectra showed a broad inertial frequency peak between 16.7 and 17.4 hr at both 22 and 90 m. The 90-m spectrum contains a 100-hr peak. The Vy spectra show an inertial peak at 16.7 hr at 22 m and one between 16.7 and 17.4 hr at 90 m. There is evidence of Lake Michigan's first free oscillation at 22 m in both the Vx and Vy spectra. The third record was obtained between December 7, 1963 and April 16, 1964 at 10 and 60 m. These winter spectra show only noise. The fourth record was gathered between May 10, 1964 and July 5, 1964, at depths of 10, 15, 22, and 90 m for the speed spectra and at depths of 15 and 90 m for the velocity component spectra. The principal peak in the speed spectra is the one near the inertial period with values of 16.4 hr at 10, 15 and 90 m and 17.5 hr at 22 m. The Vx and Vy spectra have a value of 17.5 hr at both depths for the inertial period oscillation. The spectral peak near Lake Michigan's first mode of free oscillation showed a scatter of values at 8.3 hr (15 m) and 8.5 hr (90 m) in the Vx spectrum, and 8.5 hr (15 m) and 8.9 hr (90 m) in the Vy spectrum, Figures 6-26 and 6-27.

Station 27 is located near Manitowoc on the western side of the Lake. The spectra from this station resulted from data taken from April 23, 1964 to July 10, 1964 at 15 and 22 m. The 15-m record is not reliable due to numerous zero speed readings. The 22-m speed spectrum has a 17.5-hr inertial oscillation. The Vx and Vy spectra at 22 m show the inertial oscillation at 17.5 hr. The Vx spectrum has a smaller but still significant peak at 8.6 hr which is near the first mode of Lake Michigan.

Station 29 (inertial period of 17.25 hr) is an offshore station located in the approximate center of the Lake. The data were gathered between August 20, 1963 and October 28, 1963 at four depths, 10, 15, 22, and 60 m. The speed data showed a period near the inertial frequency of 17.1 hr in the 10- and 60-m records, 17.8 hr at 15 m, and 16.4 hr at 22 m. The Vx and Vy spectra have a very distinct period at the inertial frequency of 17.25 hr at 15 and 60 m with the Vx inertial peak having slightly more energy than the Vy inertial peak, Figures 6-28 and 6-29.

Station 30 is in the middle basin of Lake Michigan, located to the east of the center of the Lake. The data were collected between December 5, 1963 and April 20, 1964. The speed spectrum for depths 15, 30, 60, 90, 120, and 150 m shows no statistically significant peaks; however, there is a concentration of energy in the long period oscillations. Several smaller peaks are computed in the velocity component spectra at depths of 30, 60, and 120 m. The questionable peaks in the Vx spectra at 25 hr in the 30- and 60-m records and 17.5 hr for 120 m and in the Vy spectra are around 20 hr in the 30- and 60-m records, and at 18.1 in the 120-m record.

Station 31 is an inshore station near Ludington on the east side of Lake Michigan. The data were collected between August 20, 1963 and November 6, 1963. The speed spectra show periods ranging from 16.1 hr at 30 m to 17.0 hr at 10 m, with values of 17.8 to 18.5 hr at 15 m, and 16.3 hr at 22 m. (See Figures 6-30, 6-31, 6-32, and 6-33.) The Vx spectra show a similar scatter at all depths instead of the usual sharply defined inertial oscillation, with 15.3 hr at 10 m, 16.1 hr at 15 m, 16.0 to 16.7 hr at 22 m, and 16.0 hr at 30 m. The Vy period estimate is also scattered, with 15.3 hr at 10 m, 17.0 hr at 15 m, 16.7 hr at 22 m, and 16.0 hr to 17.0 hr at 30 m. The problem of scattering is due to the lack of resolving power in the spectral analysis procedure; but by using harmonic analysis the scatter is resolvable.

Station 37 is a nearshore station near Sturgeon Bay on the western side of the Lake. The first set of data was collected during December 2, 1963 to April 21, 1964, for depths of 10 and 30 m. The spectra were primarily noise with energy concentrations indicated in the long period oscillations around 200 hrs. The second set of data was collected from April 20, 1964 to July 3, 1964 at 22, 30, and 60 m. The speed spectra show a peaking of energy in the periods between 14 and 25 hr, with little elsewhere. The three most significant peaks in the velocity spectra are the first free oscillation of Lake Michigan, the near-inertial period coupled with internal waves, and a long period oscillation near 100 hr. The seiche period is near 8.7 hr at 60 m in the Vx spectra and near 8.9 hr at 60 m in the Vy spectra. Those peaks near the inertial oscillation had a period of 17.4 hr at 22 m and 16.7 hr at 60 m for both Vx and Vy spectra. A long period oscillation is evident only in the Vy spectra and it is between 66 and 90 hr.

Station 38 is an offshore station in the northern basin of Lake Michigan east of Sturgeon Bay and west of the Lake's center. The data were gathered from December 2, 1963 to May 4, 1964 at 30 and 120 m. The speed spectra showed a peak at the near-inertial frequency of 17.4 hr at 120 m. The rest of the speed spectra have only noise, with energy concentration in long period oscillations. Both of the velocity spectra showed an oscillation at 16.7 hr very clearly at the 120-m depth. The Vx spectrum had a significant peak at 66 hr.

Station 39 is in the middle of the Lake west of Frankfort, Michigan. During December 4, 1962 to March 21, 1963, the speed spectrum data were collected for 90, 150 and 210 m. Large peaks are seen at 15.3 hr at 150 m and 20 hr at 210 m; however, these estimates are just indications of the periods due to the large number of zero speeds contained in the data. The second set of data was collected between August 22, 1963 and November 6, 1963 at four depths of 22, 30, 120, and 180 m. The speed spectra show broad peaks at 16.4 hr and 22 m, 15.6 hr and 30 m. The 15.3-hr peak at 120 m is very prominent and the 15.6-hr peak at 180 m is also very sharp. The Vx and Vy spectra have near-inertial periods at 16.4 hr at 22 m, 16.7 hr at 120 m with a broader peak in the Vy spectrum. The energy in the Vx spectral peak is slightly greater than in the corresponding peaks in the Vy spectra.

Station 40 is an offshore station in the northern basin west of Frankfort and east of the Lake's center. The data were gathered from January 22, 1964 to April 19, 1964 at 10, 60, and 120 m. The speed and Vx spectra are mostly noise, but a period of 17.4 hr is clearly evident in the Vy spectrum, Figure 6-34.

Station 41 is an onshore station near the east shore of the Lake near Frankfort. The data were gathered between August 22, 1963 and November 5, 1963, at four depths, 10, 15, 90, and 120 m. The speed spectra show a period of 15.3 hr at 10, 90, and 120 m; and 18.7 hr at 15 m. A large amount of energy is indicated in periods between 30 and 50 hr. The Vx spectrum shows a broad peak at 10 m between 15.3 and 16.3 hr while the Vy spectrum at this depth shows a 16.1-hr period. The Vx and Vy spectra at 90 and 120 m show a 15.3-hr period. A reliable peak of 12.5 hr appears at 90 m in the Vy data, Figures 6-35, 6-36 and 6-37.

Station 54 is located in the Straits of Mackinac between Lake Michigan and Lake Huron. The data were recorded during the fall of 1963 from September 24 to November 30 at three depths; 10, 22, and 30 m. The speed spectra have two principal peaks. The period near the inertial oscillation is estimated to be 15.3 hr at 10 and 30 m and 16.4 hr at 22 m. Peaks at 28 hours at 10 and 30 meters and 29.6 hr at 22 m are interpreted as the half period of the oscillation of Lake Michigan and Lake Huron, computed to be 56 hr. The spectra at the station are based on current speed measured by the Savonius rotor. The rotor is omnidirectional and the spectra thus appear as the half-period. The Vx spectrum has four principal peaks. The co-oscillation period of 56 hr is recorded for all depths. The diurnal period is estimated to be 21 hr for the 10- and 22-m records and 24 hr by the 30-m record. The semidiurnal period is estimated to be around 12 to 12.9 hr at all depths. The first mode of Lake Michigan appeared at 8.8 hr in the 10-m record. The Vy spectra are mostly noise and have no prominent peaks, Figures 6-38, 6-39, and 6-40.

Station 61 is located in the mouth of Green Bay. The data were recorded during the fall of 1963 from September 23 to November 29 at three depths; 10, 22, and 30 m. The chief peak at this location is around 12 hr which represents a combination of energy from the first mode of free oscillation of Green Bay and the semi-diurnal oscillation (Mortimer, 54), a conclusion verified by harmonic analysis, Figures 6-41, 6-42 and 6-43.

Summary

The data can be conveniently divided into two groups, the winter data and the summer data. The stratification of the Lake plays the dominant role in the summer data, but also affects the winter data when a deep reverse thermocline is present.

The winter data can be divided into three groups. The first group of data is that collected under an ice cover. The Lake, especially the area around stations 18 and 20 during the winter of 1962 to 1963, was under ice. Figure 6-15 has winter spectrum from station 18 during 1962-63 as an illustration of the first group and station 20, illustrates the second group using 1963-64 winter data. The inertial oscillation presumed due to the rotation of the earth is evident at both stations. The second group is comprised of data of random oscillations due to the turbulent nature of the Lake. There were no ice cover or stratification evident at the time when noise spectra were collected.

The third group of data results when there is a reverse thermocline and the internal wave oscillation causes a peak near the inertial period. Stations 38 and 39 show an inertial peak at great depths near the thermocline with winter spectra from station 38 in Figure 6-15 for the third group.

The summer data are dominated by the rotary currents largely caused by the internal waves. The first free oscillation of Lake Michigan is also readily evident along with some long period oscillations apparently due to long period meteorological disturbances. Figure 6-16 shows a typical example of summer spectral data.

Monthly Histograms

The monthly histograms provided the data for the net flow analysis. The data also provide the essential information on total flows, mean direction, and speed variations at each station. Zero values were not used in the tabulation and spurious high speed values not consistent with the station were dropped from the data.

The prime value of the histograms is to visually disclose the distribution of speed and direction over a period of time large enough to mask the long period rotations. The 17-hour period accounts for only 2.5 percent of the total time during a month and the rotations are thus effectively hidden.

Where the internal wave is most conspicuous the histograms show little net movement in any direction, Table 6-8. In the winter most stations show a to-and-fro movement if winds are variable, but are unidirectional if winds are dominant from one quadrant. Along the shore, during winter and summer, movements are usually binodal. In general currents parallel the axis of the Lake. The only major exception appears in the ridge area between Milwaukee and Muskegon.

Speed profiles for currents are normally smooth, peaking in the vicinity of the average speed of the station and decreasing out to a maximum speed (Verber, 89). Ninety histograms were examined and summer speeds were normally greater than winter speeds at depths from 10 to 60 m. Below this depth, the winter speeds were greater.

Station 61, in the channel between Green Bay and Lake Michigan had unusually low values for all three meters compared to other stations in the Lake. If such speeds had occurred at one level the rotor values would have been suspect, but the speeds were uniform within the column.

Station 54, in the Straits of Mackinac, had the highest individual speeds, over 60 cm/sec, in the Lake. The average speed, near 20

TABLE 6-8

HISTOGRAM

STATION 9, 15 METERS

OCTOBER 1-17, 1963

SPEED IN CM/SEC

ANGLE	4.5	13.5	22.5	31.5	40.5	49.5	NUMBER	FLOW
0	11	27	25	13	4	1	81	1603.5
30	9	30	25	24	5	0	93	1984.5
60	15	35	25	21	2	0	98	1872.0
90	11	35	33	16	2	1	98	1922.0
120	11	29	35	12	4	0	91	1786.5
150	7	39	51	25	3	0	125	2554.5
180	4	34	56	25	1	0	119	2515.5
210	3	39	46	17	2	0	107	2110.5
240	8	43	40	19	3	0	113	2227.5
270	11	46	24	11	1	0	93	1573.5
300	10	28	16	23	5	0	82	1701.0
330	15	26	28	14	4	1	88	1707.0
TOTALS	114	411	404	220	36	3	1188	

cm/sec, was not exceptionally greater than for stations 8 or 9 during the summer. In general, speeds on the eastern side of the Lake (near the shore) averaged 4 to 5 cm/sec higher than the speeds on the western side. Stations near shore did not show unusually higher speeds than the offshore stations.

Six-Hour Averages

Some of the most useful data programmed for analysis work were the 6-hour averages. Periodic functions in Lake Michigan are usually 18 hours or more and thus not completely obscured by the averages. Similarly, long-term trends can be readily displayed without a mass of detail. Daily averaging (24 hours) produces spurious results from the summer data because of the averaging of the 18-hour inertial period. The result is a fictitious 90-hour period.

Phenomena which occur over a 3-to-4-day period, such as current speed responses to winds, are readily disclosed by plotting (Verber, 89). Table 6-9 illustrates 6-hour data from one station. The summer data include the average of 18 readings where all data were valid and 12 readings for the winter period. If speeds go to zero, the vane reading is not included. A continuous plot of the 6-hour averages, speeds and direction, was made for some analysis work. The effect of rotary currents, produced by the internal wave is readily disclosed by the plots.

Plotting of 6-hour average current speeds indicates that responses to wind energy can be traced from station to station and depth to depth without difficulty. Current speeds at a station have been traced from the shore and across the Lake and for more than 200 km in a north-south direction. Although current speeds show a direct response to wind stress (within 2 hours), the response to a change in direction is not well established in mid-lake. The drogue study data included at least three abrupt wind shifts, runs 3, 5, and 6. The 6.1-m drogues were not affected by a wind shift on run 5, even after several hours. It is believed that topography was the primary influence in maintaining the direction. Wind shifts in run 3 indicated no shift in current direction at 1.5 meters at the end of 1.25 hours. The study was terminated at that point. On run 6, the current shifted with the wind within an hour whereas the 6.1-meter currents did not show any abrupt shift.

Responses of current direction change to wind shifts are slow. Within the Lake proper one must consider the previous wind regime, as the force which must be changed, the newly applied force, and its areal extent. The work by Ayers et al. (2), using a geometric series on the winds is an attempt to uncover these relationships.

TABLE 6-9

LAKE MICHIGAN SIX-HOUR AVERAGE WINDS

STATION 54

			0		6		12		18	
Month	Day	Yr	An*	Sp**	An	Sp	An	Sp	An	Sp
9	26	63	22	12	24	13	24	13	25	8
			15	7	22	13	28	18	35	11
9	28	63	9	13	11	14	12	17	9	16
			1	12	36	11	31	9	29	13
9	30	63	26	16	33	9	26	6	20	7
			20	11	21	13	22	18	20	16
10	2	63	21	20	23	15	24	12	28	13
			30	17	34	14	32	16	33	11
10	4	63	4	7	19	7	25	12	22	8
			19	5	21	12	23	13	18	6
10	6	63	21	12	22	15	23	26	28	10
			35	7	32	10	29	14	30	14
10	8	63	30	12	28	6	27	7	23	7
			20	7	20	4	25	12	22	5
10	10	63	16	3	19	3	27	9	19	4
			6	8	2	9	3	6	35	12
10	12	63	33	10	30	6	25	12	25	13
			22	7	22	9	24	19	23	12
10	14	63	23	18	24	16	25	13	25	8
			23	5	24	7	31	9	13	5
10	16	63	12	6	21	7	28	7	25	5
			9	4	9	7	27	5	21	3
10	18	63	14	3	10	4	1	5	10	5
			15	5	17	6	28	9	22	5
10	20	63	25	7	28	5	33	4	33	7
			8	16	10	20	11	22	12	25
10	22	63	14	15	16	10	26	7	28	5
			21	9	21	7	26	10	12	8
10	24	63	20	8	18	11	21	13	18	7
			19	14	21	11	23	15	24	9
10	26	63	22	8	19	12	23	15	29	10
			31	12	30	12	25	15	28	10
10	28	63	34	8	33	8	33	8	36	11
			0	9	1	10	35	9	35	10

*Angle in tens of degrees.
**Speed in cm/sec.

Station 7 near the shore, and station 8, approximately 34 km east of station 7, were compared for responses to wind shifts. Winds at station 8 were used as being representative for the area.

Of the four wind shifts observed, which were due to frontal passages, station 7 responded in every instance as shown by the 6-hour data. Station 8, dominated by rotary currents, continued to rotate, with increased speeds, but the residual current did not change direction.

Station 7 reacted to the wind shifts in 18 to 30 hours depending on the speeds of the wind. It is apparent from the 2-hour records that the changes or response times occur much more quickly than the averages indicate.

Two-Hour Envelopes

The 2-hour maximum and minimum values show the great stability in water movements. No great changes occur within short (2-hour) periods of time and complete shifts usually take more than 12 hours. The rotary current, approximately 17 to 18 hours, usually represents the greatest or most rapid reversal in direction for currents in mid-lake. Complete reversals in the upper layers may occur in 1 or 2 hours near the shore, as indicated by the drogues. It may take up to 18 hours for the entire column of water to reverse direction.

The most significant use of the 2-hour envelopes is for visual interpretation (see illustrations in Chapter 10). Problems of blurring, extraneous high speeds, periodic changes, daily fluctuations, and other features are seen instantly. Thirty centimeters (12 inches) of the complete printout represents 5 days which include more than 300 data points.

The summer current data in mid-lake (and some inshore stations) are usually dominated by the internal wave and exhibit some rotary motion. Stations 8 and 9, where the internal waves exert their purest influence, have shown continuous rotary motion for more than 40 days' duration. Both direction and speed illustrate the undulating or rotary form. Verber (90) indicates the presence of five types of flow normally found in the Lake. Straight line flow is most prevalent in winter and at selected areas in summer, such as nearshore flows and channels. All other types of flow in summer are some form dominated by the internal waves. Rotary motion in winter can be due to the deep internal wave on the reverse thermocline or to true inertial motion.

The visual display of the 2-hour envelopes makes them more valuable than the 6-hour envelopes.

Flow at Straits of Mackinac

Station 54 is located in the Straits of Mackinac, and current meter records are available for approximately a 1-month period -- from the last week in September through the month of October 1963. The station was first instrumented in December 1962, with intended recovery in May 1963, but unfortunately those meters were lost. Summarized results from the October 1963 record are given in Table 6-11 and on Figure 6-44.

Current through the Straits reverses approximately every 26 hours, due to the Lake Michigan-Lake Huron 51-hour seiche. The nodal point of the seiche is at the Straits and here the currents would be strongest. Speeds in excess of 60 cm/sec are common in the record, and speeds exceeding 30 cm/sec occurred 23 percent of the time. Table 6-11 shows the average speeds during the 1-month record, at each of the three depths where meters were located and for both eastward and westward flow.

For translating the velocity readings into volumetric rates of flow, the cross sectional area of the Straits was divided into three parts and apportioned among the three current meters at station 54 in the percentages shown in Table 6-10. The resulting calculated flow rates are shown on Figure 6-44. The net outflow shown on the graph is about 1,500 cubic meters per second for the period of record. As the graph also shows, short-term flow rates approaching 20 times this magnitude occur both into and out of Lake Michigan. Thus the periodic seiches provide a mechanism for the exchange of large volumes of water between Lakes Michigan and Huron.

Summary of Lake Currents

The data from Lake Michigan disclose that a simple pattern of net circulation does not exist in summer, but that one can be identified in winter.

Movements close to the shore are fairly stable in both winter and summer and respond to the winds prevailing over the Lake. In general, the shore currents move northward on both sides of the Lake except for periods during the late fall, winter, and early spring. During these periods more northerly winds prevail. The currents in the western part of the Lake are noticeably slower than those in the eastern part, except when northeasterly winds prevail. Average speeds on the western side of the Lake range from 5 to 10 cm/sec while those on the eastern side range from 12 to 14 cm/sec.

Inshore and offshore currents are quite separate from one another. Offshore patterns are governed in the winter by long-term wind

TABLE 6-10

CROSS SECTION OF THE STRAITS OF MACKINAC

SECTION	DEPTH IN METERS		AREA IN SQUARE METERS	PERCENT OF TOTAL
Top	15		68,560	61.5
Mid	12		24,190	21.7
Lower	37		18,730	16.8
	64	Total	111,480	100.

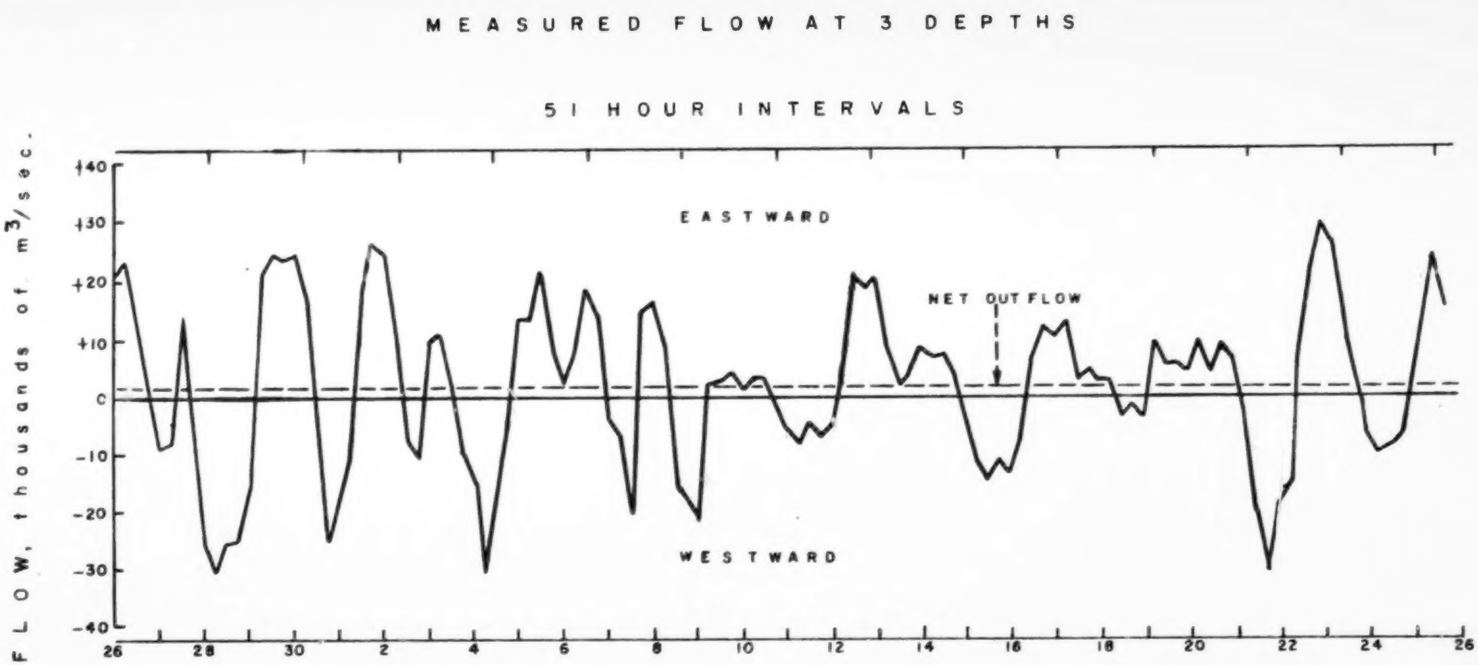
TABLE 6-11

AVERAGE SPEED AND DIRECTION IN THE STRAITS

SECTION	EASTWARD		WESTWARD	
	ANGLE	CM/SEC	ANGLE	CM/SEC
Top	276°	20.05	120°	20.66
Mid	291°	20.80	99°	16.58
Lower	271°	14.45	112°	13.71

MEASURED FLOW AT 3 DEPTHS

51 HOUR INTERVALS



OCTOBER 1963

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

**FLOW AT STRAITS
OF MACKINAC**

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 6-44

movements and pressure patterns. During the summer the internal wave so overshadows all other features that the external effects are obscured except in the current speeds. The internal waves produce a rotary motion in the currents with a 17- to 18-hour period. In general, epilimnion and hypolimnion flow are opposed in direction (180° out of phase). The opposing phase relationship applies only to the rotary motion and not to the net flows. In a few instances certain layers within the hypolimnion will not be a perfect 180° opposite to the epilimnion. These cases occur when external pressures produce an oscillatory current rather than a spiral flow. Although the currents are out of phase during part of the cycle, the oscillatory current does not complete a full 360°. This shift of flow can occur in the epilimnion as well as the hypolimnion. Net flows, over a month period, may be in the same direction from the surface to great depths. In winter the vertical profile indicates that extremely large masses of water will react together and to 100 or more meters in depth.

In the summer the net circulation in the Lake breaks down into cells which are largely controlled by standing internal waves. As it takes time, after wind disturbance, to build up standing oscillations, and as a mixture of waves of differing nodality may be present, each decreasing in amplitude at a different rate, the boundaries of the cells will not be rigidly fixed and the picture is likely to be complex. In inshore waters, constraint and friction imposed by boundaries and shallow depth lead to a different current regime, with flow predominantly parallel to the shore, and internal waves are not so evident in these waters.

CHAPTER 7

TEMPERATURE STUDIES

Introduction

Knowledge of temperatures within the waters of a lake, and of variations in water temperature with respect to both time and place, yields valuable insight into such phenomena as density stratification, extent and effectiveness of mixing, and consequent variations in water quality.

This section presents the results of temperature observations in Lake Michigan, a review of and comparison with recorded previous studies and the conclusions which may be drawn concerning temperature regimes and their influence on water movement and mixing.

Field observations of temperature changes in Lake Michigan began in September 1961, and continued on an intermittent basis until September 1963. Temperature profiles were made throughout the Lake at the water quality sampling station sites during cruises 1 to 8 and 10 through 18. Bathythermograph (BT) measurements were also made in the deeper portions of the Lake during the fall and winter of 1961-62 during cruises 50 through 52.

Definitions

Stratification occurs in a lake when its waters are divided into layers having identifiable differences in temperature, density, or other characteristics with rather sharply defined boundaries or zones of transition between layers. Thus, a lake in which the temperature was either constant or varied uniformly from top to bottom would not be thermally stratified. A deep lake in the temperate zone usually stratifies during the summer and may stratify during the winter. Very shallow lakes rarely stratify, due to constant mixing from top to bottom by wind action. However, during prolonged calm periods in mid-summer, even shallow lakes will stratify for short periods of time. A typically stratified lake is divided into three thermal zones: the top zone, called the epilimnion; the bottom zone, called the hypolimnion, and a zone of rapid temperature change called the thermocline. The thermocline is normally defined as any abrupt change in temperature between two vertically separated masses of water of different temperature. There may also be secondary thermoclines, where more than one exists; the winter thermoclines, where colder but less dense water lies over warmer but denser water; and pseudo or false thermoclines, sometimes produced by unusual local conditions.

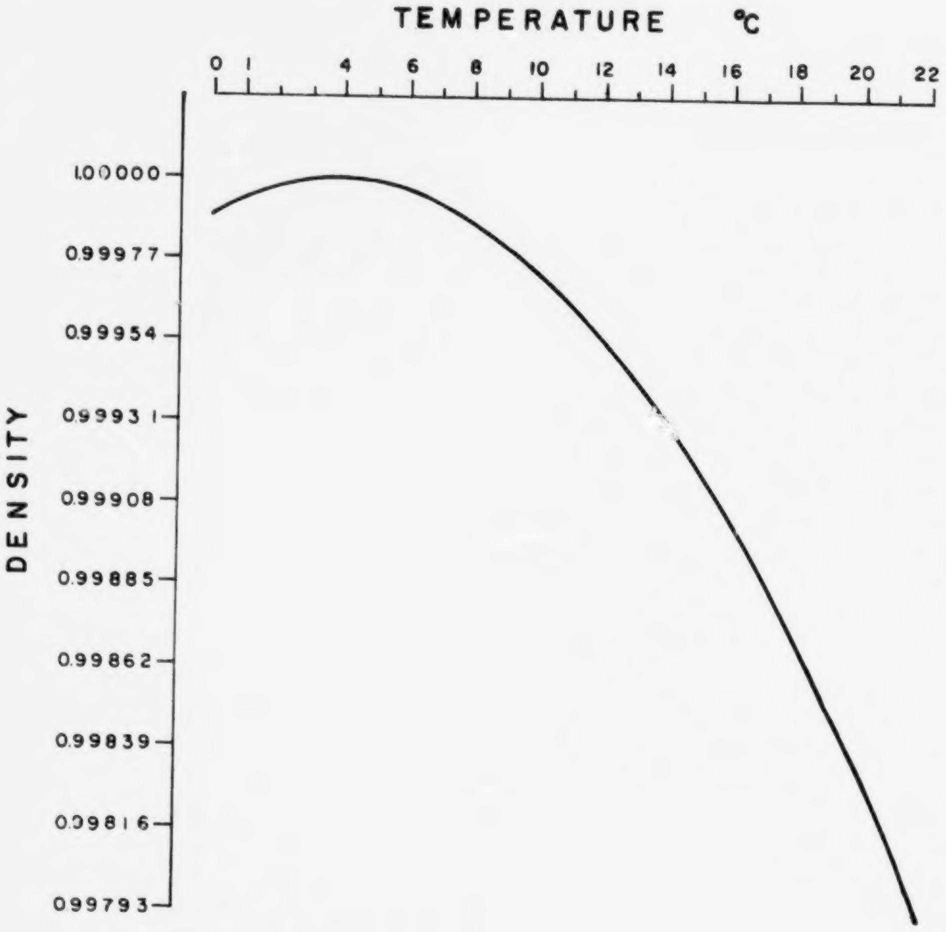
In Lake Michigan the epilimnion varies from a few meters thickness in late spring or early summer to over 61 meters in late fall. The thermocline normally is about 6 meters thick but can be over 15 meters in thickness or as little as 1 meter (during storm periods; see Figure 10-1). The hypolimnion encompasses all the water below the thermocline.

An overturn is a descriptive term denoting vertical mixing or circulation from top to bottom of the entire lake. If the lake is shallow a complete overturn may occur. Lakes which are extremely deep or sheltered from the wind may only experience a partial or incomplete overturn. An overturn occurs when the lake is isothermal and, therefore, of the same density. According to Welch (92) the thermal resistance under such conditions is at a minimum and relatively light winds could cause complete circulation. Most lakes in the temperate zone have an overturn in the spring and fall. In Lake Michigan a fall overturn occurs in the southern basin when the Lake begins to cool, and is characterized by the sinking and mixing of cold, dense water from the surface, displacing the warmer and lighter water below. Cooling continues until the Lake reaches the temperature of maximum density and the water mass offers little resistance to mixing from the wind energy imparted by late fall storms. Figure 7-1 shows the temperature-density curve for fresh water. In the deeper northern basin of Lake Michigan, the bottom portion of the Lake remains permanently at the temperature of maximum density. The temperature of maximum density of water varies with pressure and therefore with depth, being about 4°C at the surface and decreasing about 0.06°C per 31 meters of depth (see Eklund, 29). This zone of constant temperature was found to extend from the 183-meter level downward during the period of observations. The level probably varies from year to year depending on the severity of the winter. A spring overturn occurs in the southern basin of Lake Michigan when the surface water temperature rises to 4°C and the denser surface water sinks through the less dense layers below. In the northern basin there is also a partial overturn.

A thermal bar or barrier, as described by Rodgers (68), occurs in both spring and fall. This bar appears to inhibit or restrict mixing between the nearshore and offshore waters during the few weeks it is in existence. A sharply defined thermal barrier was found during the 1961-1962 bathythermograph studies in the Milwaukee region. Records indicate that the bar or a condition similar to it may occur at any time of the year.

Previous Studies

Five important studies on the temperatures of Lake Michigan have been published. In addition, hundreds of observations are being taken every day at water intakes by the plant operators. The bulk of these



NOTE
Welch, reference 10, page 350

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

DENSITY OF FRESH WATER

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-1

data normally is not published and thus not readily accessible for general use. Several thousands of observations have been made over the past 15 to 20 years by research groups or other interested agencies for application to other problems, such as biological studies. The U. S. Navy made observations during World War II in its submarine tests in Lake Michigan (Hough, 40). The Great Lakes Research Institute of the University of Michigan and the U. S. Bureau of Commercial Fisheries at Ann Arbor, Michigan have collected and filed several thousands of temperature soundings.

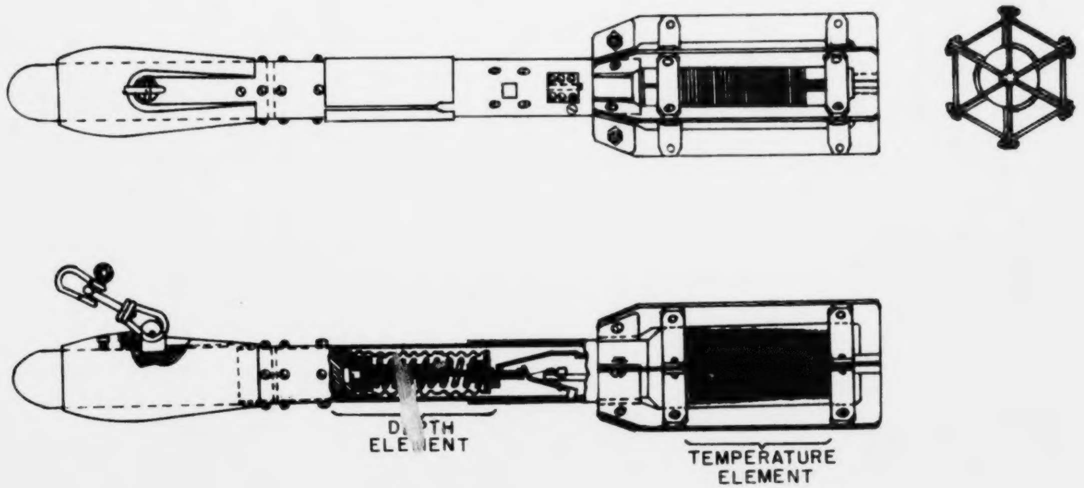
The five principal published studies on Lake Michigan are: Van Oosten (84), Church (18, 19), Millar (52) and Ayers et al. (2). Van Oosten carried out most of his work in 1930-32 but the data were not published until 1960. The work by Church (18, 19) in the 1940's is probably the most comprehensive published to date, covering all of the seasons of the year. Millar's studies were for the surface waters of the Lake and utilized the temperature recordings from ship's intakes. The study does not include the mid-winter period. Ayers et al. presented detailed temperature profiles for various sections of the Lake during four synoptic cruises in the summer of 1955. Van Oosten lists several of the minor published studies on temperature in Lake Michigan. Moffett (53) has detailed an instance of upwelling on the east shore of Lake Michigan; and Mortimer (54) has assembled and interpreted summer temperature records from 15 waterworks intakes.

Although many studies of temperature have been made in Lake Michigan there has been a paucity of data for the winter period and specifically from the deeper parts of the Lake.

Methods of Study

Instruments

The investigation by the Great Lakes-Illinois River Basins Project utilized the instruments discussed below. The bathythermograph (Figure 7-2) was invented and first described by Spilhaus (73). The instrument was not generally available until the end of World War II, and even then the cost was still prohibitive for its general usage. A description of its operation and capabilities has been published by Bralove (14). The most accurate of all thermometers is the reversing thermometer, often called a deep-sea thermometer. A detailed description and specifications have been reported by Welch (92). A hand thermometer, of the armored type, is used for calibration of the BT. The temperature recorder, Figure 7-3, developed at the Woods Hole Oceanographic Institution, has been designed for long periods of recording, unattended, and at great depths (Feyling, 32).


DEPTH ELEMENT
TEMPERATURE ELEMENT

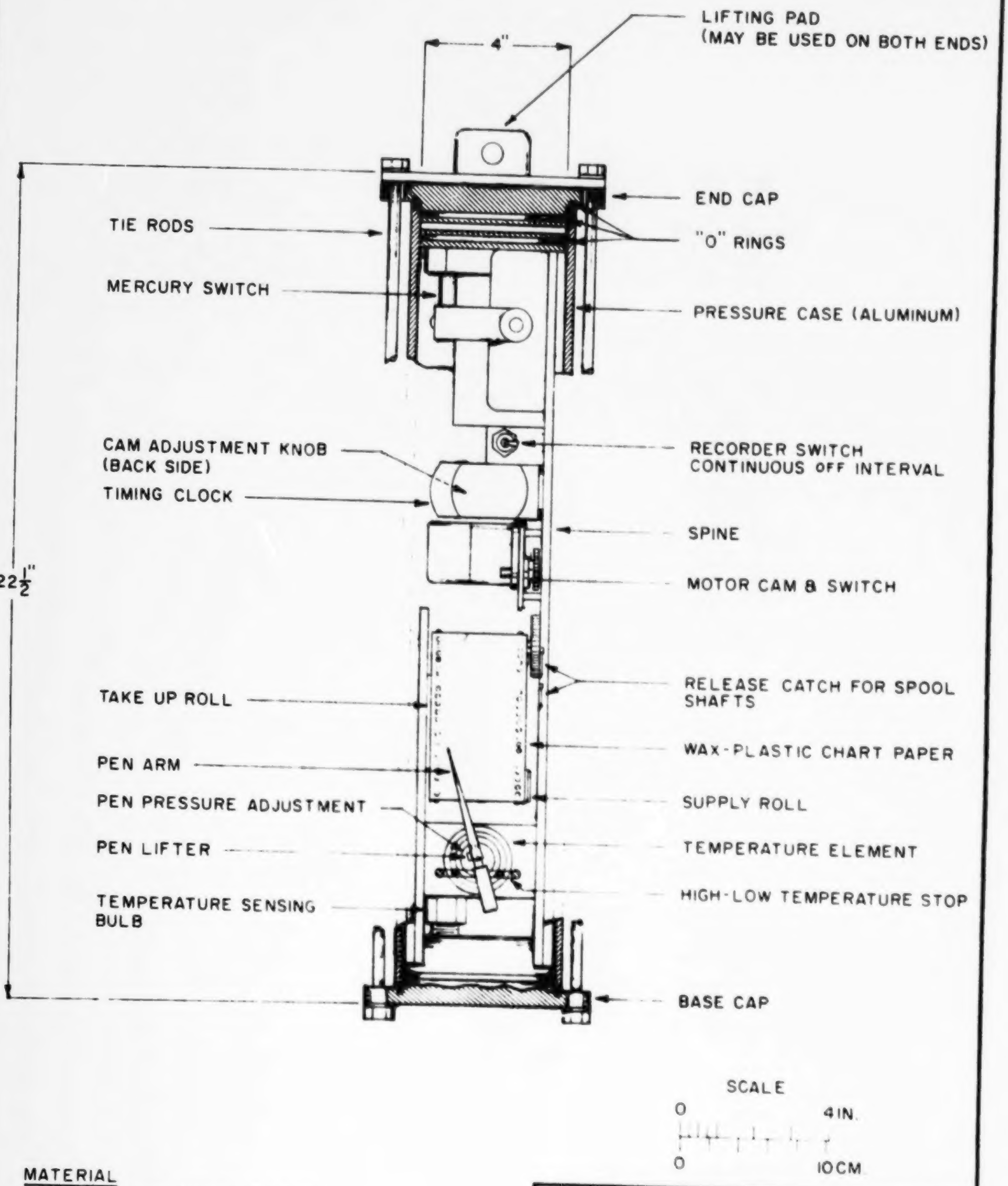
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

BATHYTHERMOGRAPH

NOT TO SCALE

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-2


LIFTING PAD
(MAY BE USED ON BOTH ENDS)
4"
END CAP
TIE RODS
"O" RINGS
MERCURY SWITCH
PRESSURE CASE (ALUMINUM)
CAM ADJUSTMENT KNOB
(BACK SIDE)
RECORDER SWITCH
CONTINUOUS OFF INTERVAL
TIMING CLOCK
SPINE
22 1/2"
MOTOR CAM & SWITCH
RELEASE CATCH FOR SPOOL SHAFTS
TAKE UP ROLL
WAX-PLASTIC CHART PAPER
PEN ARM
SUPPLY ROLL
PEN PRESSURE ADJUSTMENT
PEN LIFTER
TEMPERATURE ELEMENT
TEMPERATURE SENSING BULB
HIGH-LOW TEMPERATURE STOP
BASE CAP
SCALE
0
4 IN.
0
10 CM.

MATERIAL

ALUMINUM & STAINLESS STEEL

FINISH

OXIDE FINISH & YELLOW EPOXY PAINT
ON ALUMINUM PARTS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TEMPERATURE RECORDER

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region
Chicago, Illinois

FIGURE 7-3

In general, the instruments have the following ranges of accuracy:

TABLE 7-1

DEGREE OF ACCURACY OF INSTRUMENTS

INSTRUMENT	RANGE IN °C
Hand Thermometer	± 1.0
Thermometer Recorder	± 0.25
Bathythermograph	± 0.1
Reversing Thermometer	± 0.01

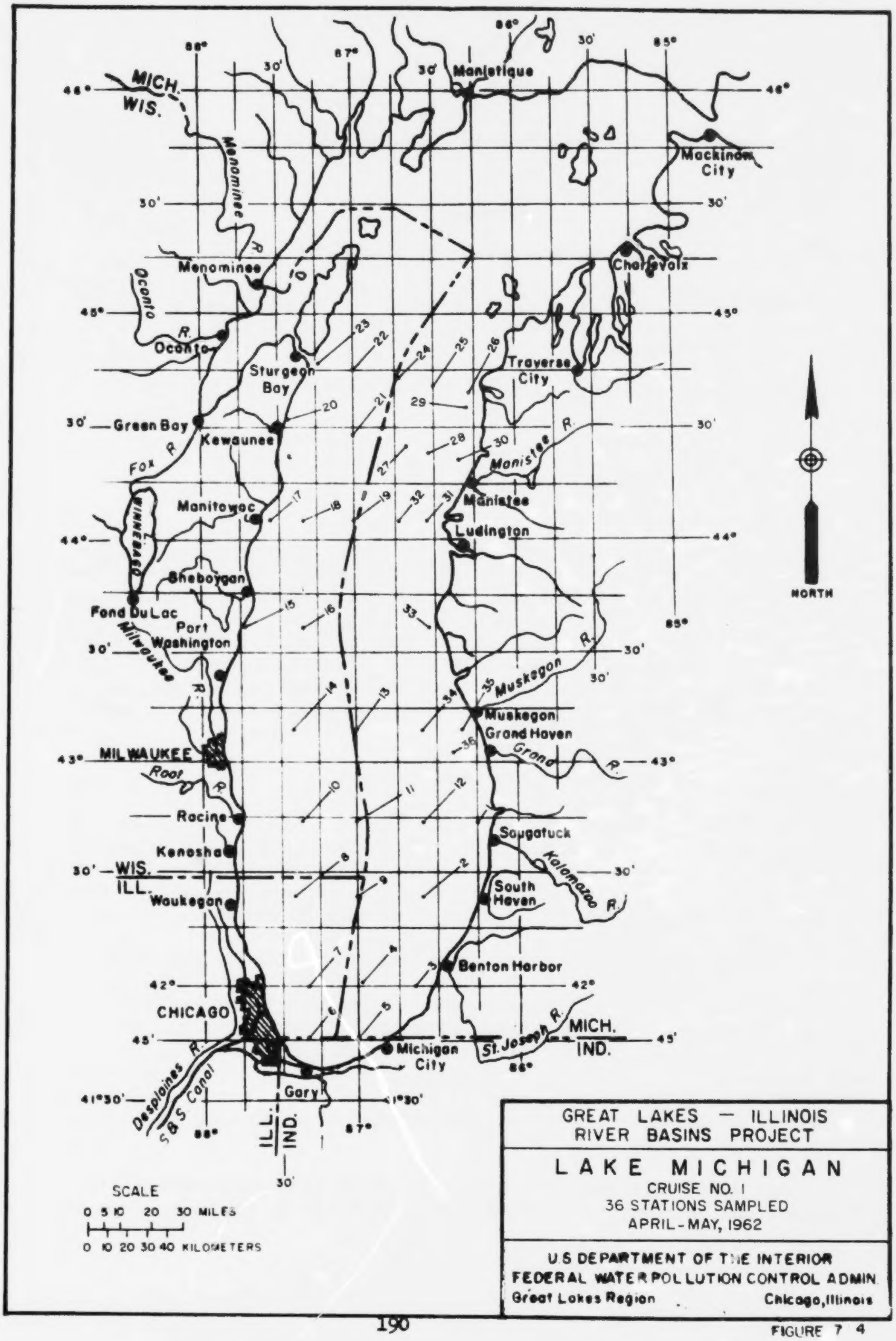
The BT is useful in obtaining a complete temperature profile, taking a few minutes of time, in depths over 200 meters of water. The reversing thermometer can get accurate temperatures at one depth (such as a sampling depth) in a period of 3 to 4 minutes. A series of these instruments is frequently used on a single line. The temperature recorder can be placed at a specific depth and set to record the temperature every 20 or 30 minutes on a strip-chart for periods as long as 6 months. Such recorders were used in conjunction with current meters in the Great Lakes studies.

Bathythermograph Surveys

Beginning in September 1961, the Project began intermittent BT soundings on all cruises in the Lake. The last continuous cruise to collect BT data was number 18 which ended in September 1963. Approximately 1,300 BT records were taken and read. Figures 7-4 to 7-27 show the map locations and Table 7-2 gives an example of the data.

Regular lakewide cruises were made by the Project from the spring of 1962 through 1963. These were identified as cruises 1 to 18, see Table 7-3. Since many temperature records were taken prior to the regular scheduled cruises, they were identified as 50, 51, and 52. Cruise 50 was principally in the south basin in 1961. Cruise 51 was all in the deepest portions of the northern basin and cruise 52 was in the southern basin early in 1962. Special attention was given to the winter of 1961-62 to determine if winter stratification existed in the Lake and if so, to what depth.

All data were read at 3-meter (10 feet) intervals for the first 31 meters and at 6-meter intervals (20 feet) to 61 meters. From 61

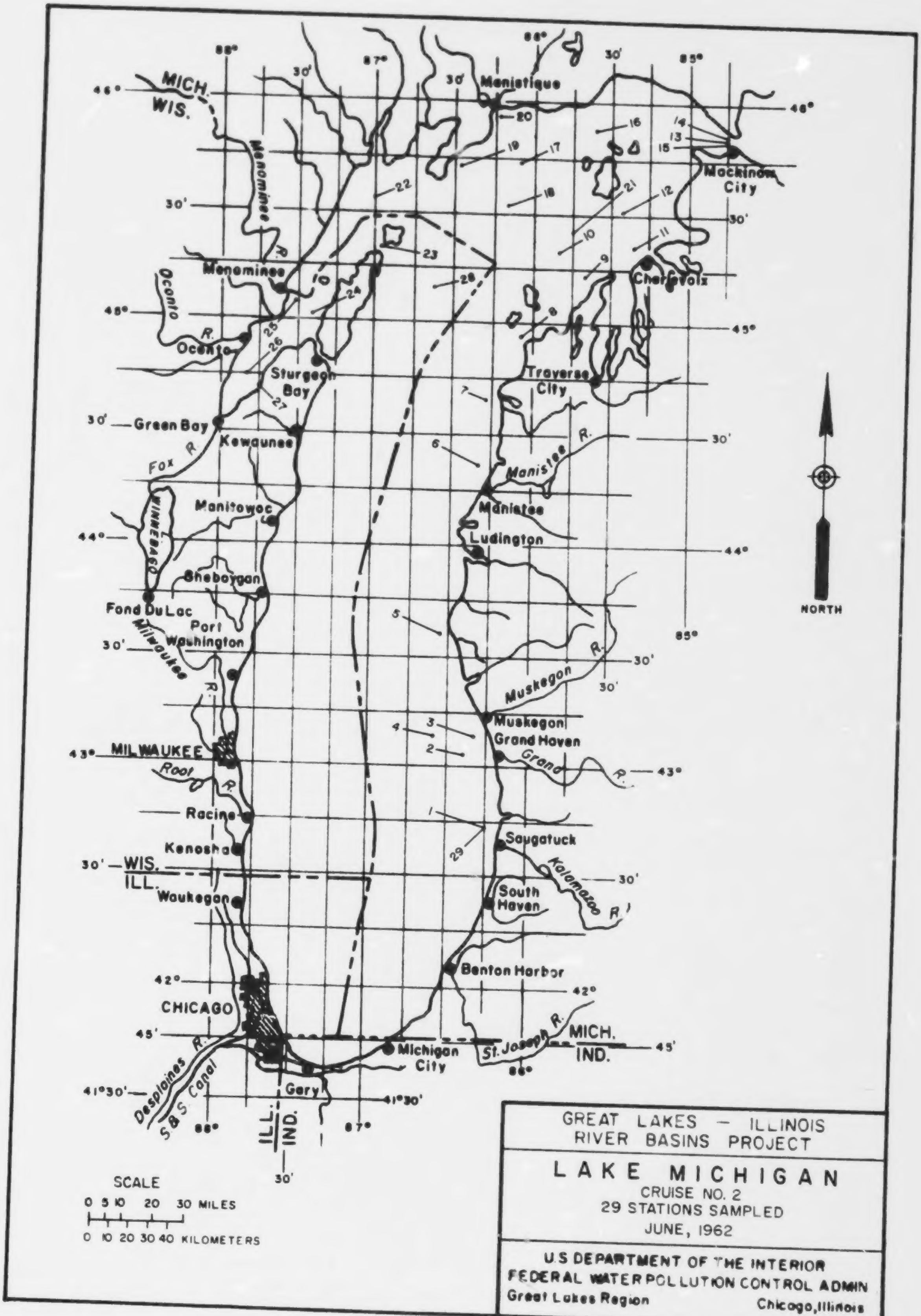

88°
30'
87°
30'
86°
30'
85°
46°
45°
44°
43°
42°
45'
41°30'
MICH.
WIS.
Manistique
Mackinaw City
Menominee R.
Menominee
Oconto R.
Oconto
Charlevoix
Sturgeon Bay
Traverse City
Green Bay
Kewaunee
Fox R.
Winnebago
Manistee R.
Manistee
Manitowoc
Ludington
Sheboygan
Fond Du Lac
Port Washington
Milwaukee R.
Muskegon R.
Muskegon
Grand Haven
Grand R.
MILWAUKEE
Root R.
Racine
Kenosha
Saugatuck
Kalamazoo R.
WIS.
ILL.
Waukegan
South Haven
Benton Harbor
CHICAGO
St. Joseph R.
MICH.
IND.
Michigan City
Desplaines R.
S & S Canal
Gary
ILL.
IND.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
NORTH
SCALE
0 5 10 20 30 MILES
0 10 20 30 40 KILOMETERS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 1
36 STATIONS SAMPLED
APRIL-MAY, 1962

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7 4


MICH.
WIS.
Menominee R.
Manistique
Mackinaw City
Menominee
Oconto R.
Oconto
Sturgeon Bay
Green Bay
Kewaunee
Fox R.
Winnebago
Manitowoc
Sheboygan
Fond Du Lac
Port Washington
Milwaukee R.
MILWAUKEE
Root R.
Racine
Kenosha
WIS.
ILL.
Waukegan
CHICAGO
Desplaines R.
S.&S. Canal
Gary
ILL.
IND.
Michigan City
St. Joseph R.
MICH.
IND.
Benton Harbor
South Haven
Kalamazoo R.
Saugatuck
Grand R.
Grand Haven
Muskegon
Muskegon R.
Ludington
Manistee
Manistee R.
Traverse City
Charlevoix
NORTH
88°
87°
86°
85°
46°
45°
44°
43°
42°
30'
45'
41°30'
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
SCALE
0 5 10 20 30 MILES
0 10 20 30 40 KILOMETERS

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 2
29 STATIONS SAMPLED
JUNE, 1962

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region
Chicago, Illinois

FIGURE 7-5

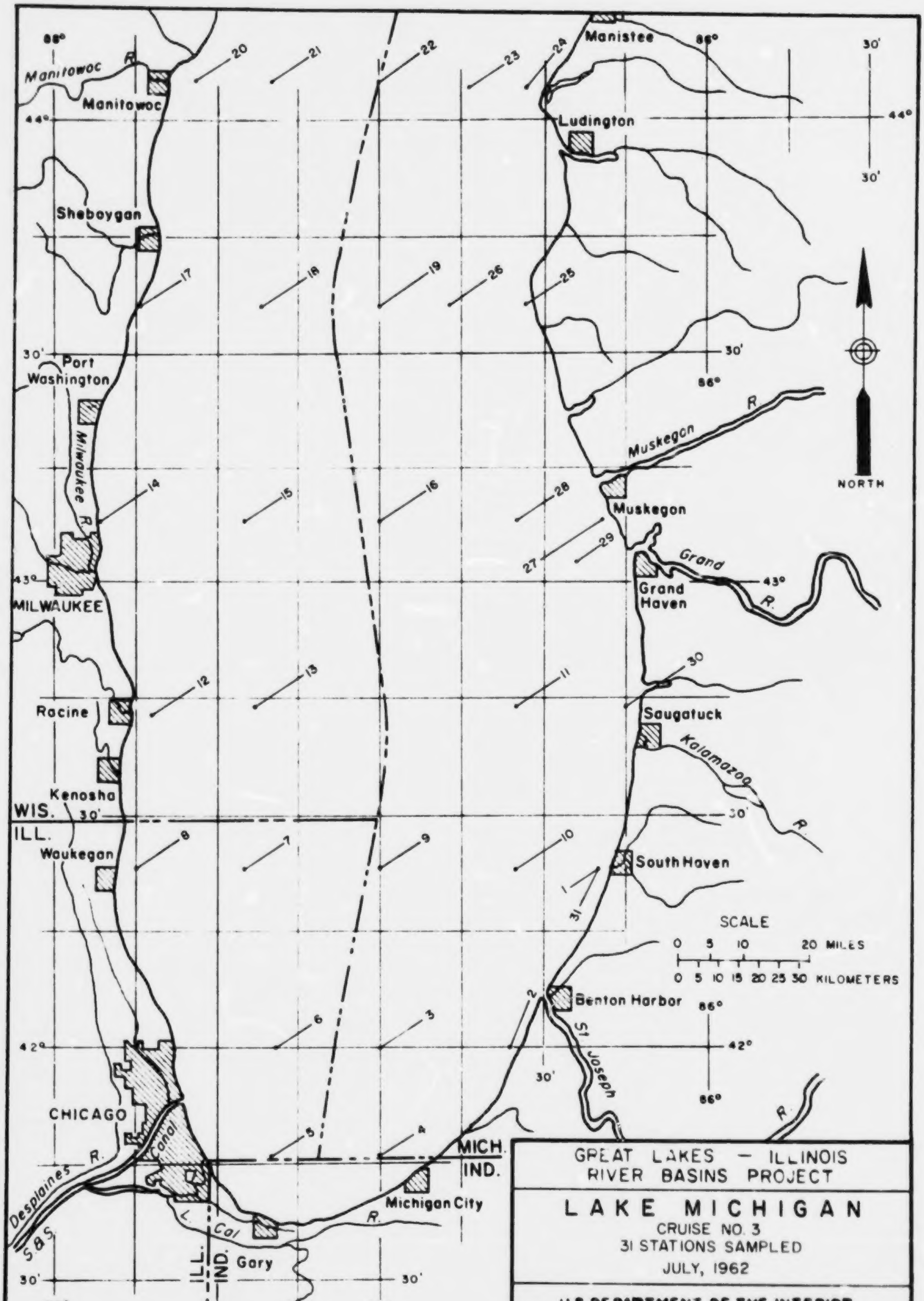
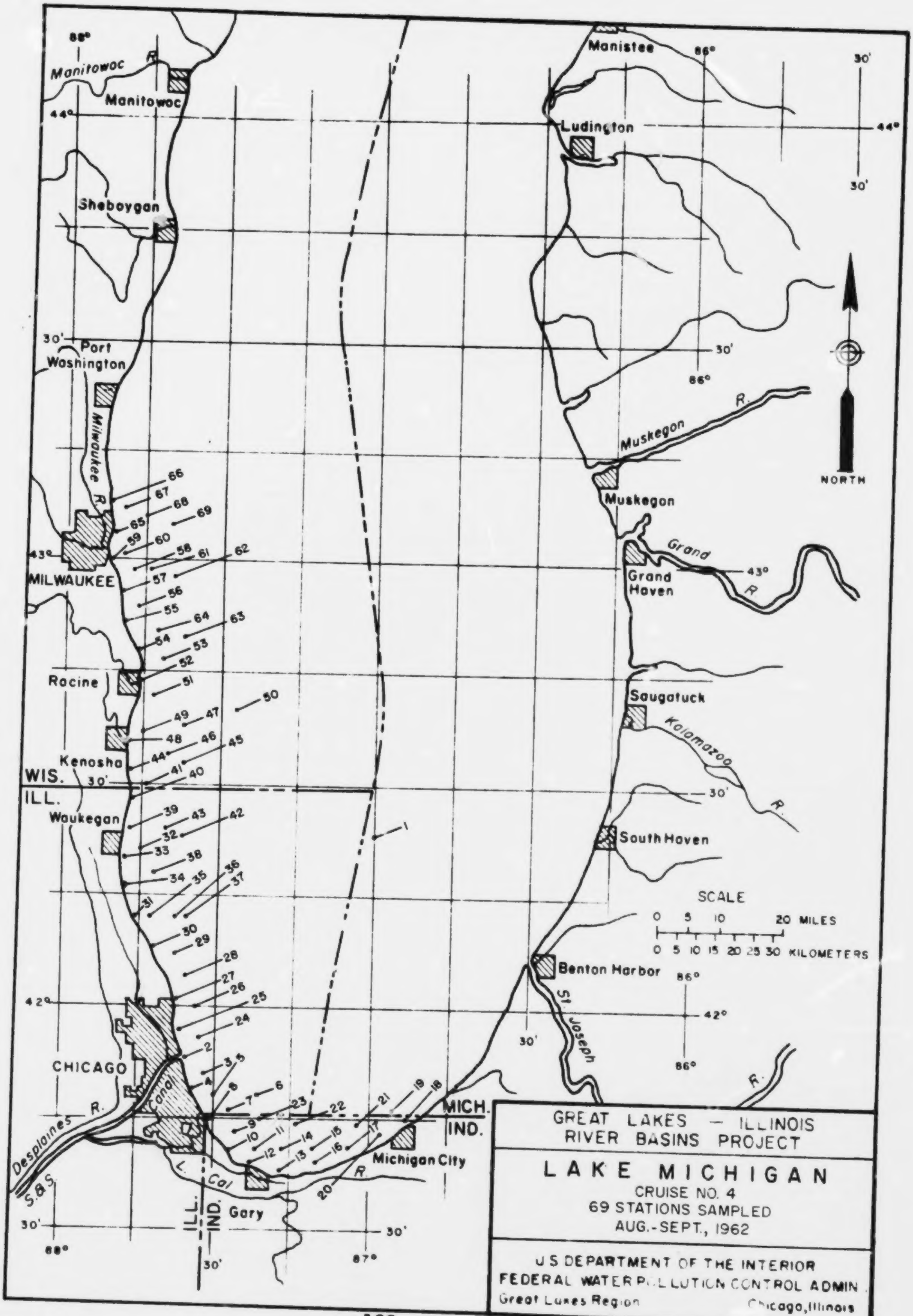

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT
LAKE MICHIGAN
CRUISE NO. 3
31 STATIONS SAMPLED
JULY, 1962
U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region
Chicago, Illinois
Manitowoc R.
Manitowoc
Sheboygan
Port Washington
Milwaukee R.
MILWAUKEE
Racine
Kenosha
WIS.
ILL.
Waukegan
CHICAGO
R.
Canal
Desplaines
S.B.S.
L. Cal R.
Gary
ILL.
IND.
MICH.
IND.
Michigan City
Benton Harbor
St Joseph
R.
South Haven
Kalamazoo R.
Saugatuck
Grand R.
Grand Haven
Muskegon
Muskegon R.
Ludington
Manistee
NORTH
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
88°
87°
86°
44°
43°
42°
30'
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

FIGURE 7-6

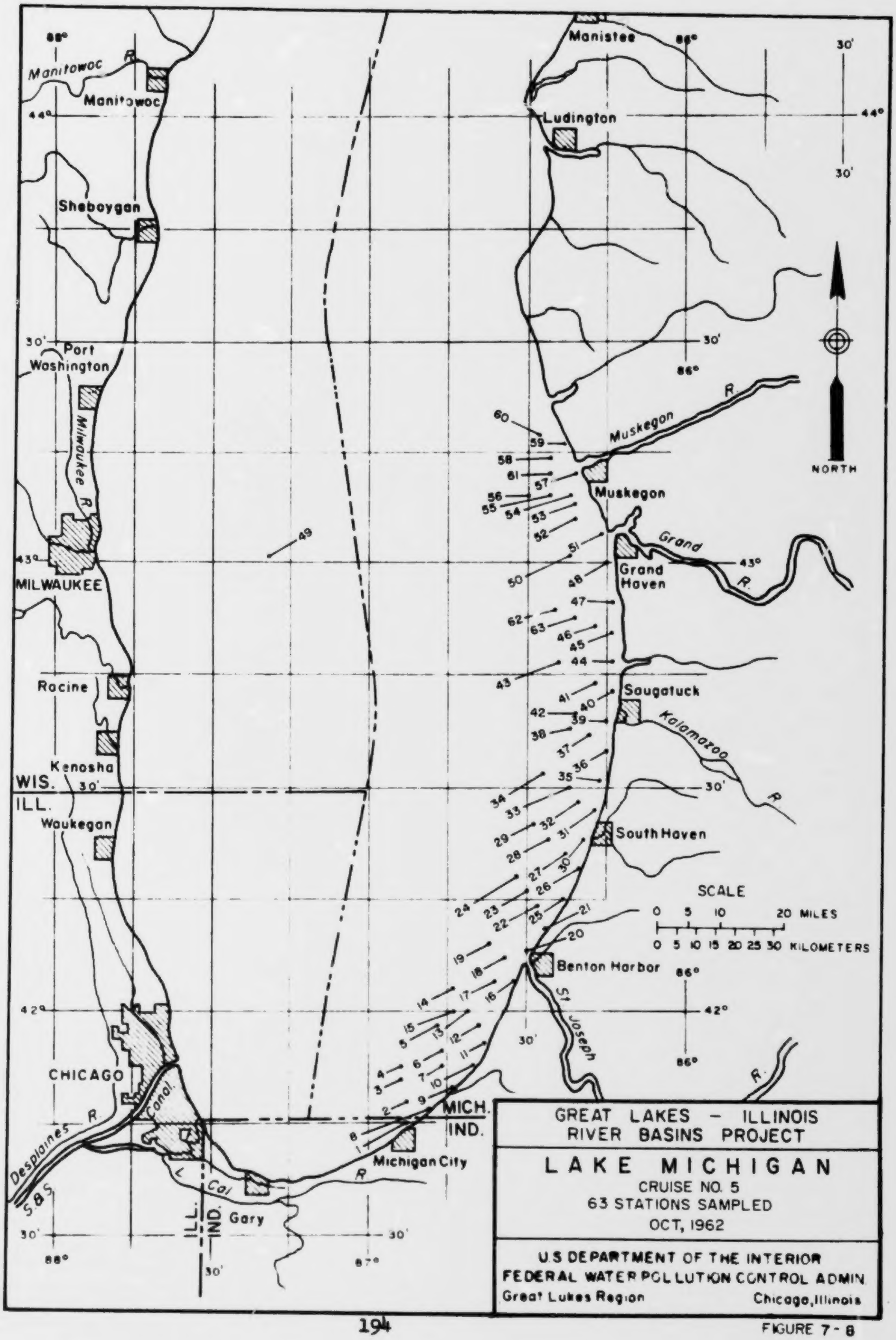

Manitowoc R.
Manitowoc
Manistee
Ludington
Sheboygan
Port Washington
Milwaukee R.
MILWAUKEE
Racine
Kenosha
WIS.
ILL.
Waukegan
CHICAGO
Desplaines R.
Canal
S.B.S.
L. Cal R.
Gary
ILL.
IND.
MICH.
IND.
Michigan City
Benton Harbor
St Joseph R.
South Haven
Kalamazoo R.
Saugatuck
Grand Haven
Grand R.
Muskegon
Muskegon R.
NORTH
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
88°
87°
86°
44°
43°
42°
30'

GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 4
69 STATIONS SAMPLED
AUG.-SEPT., 1962

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-7

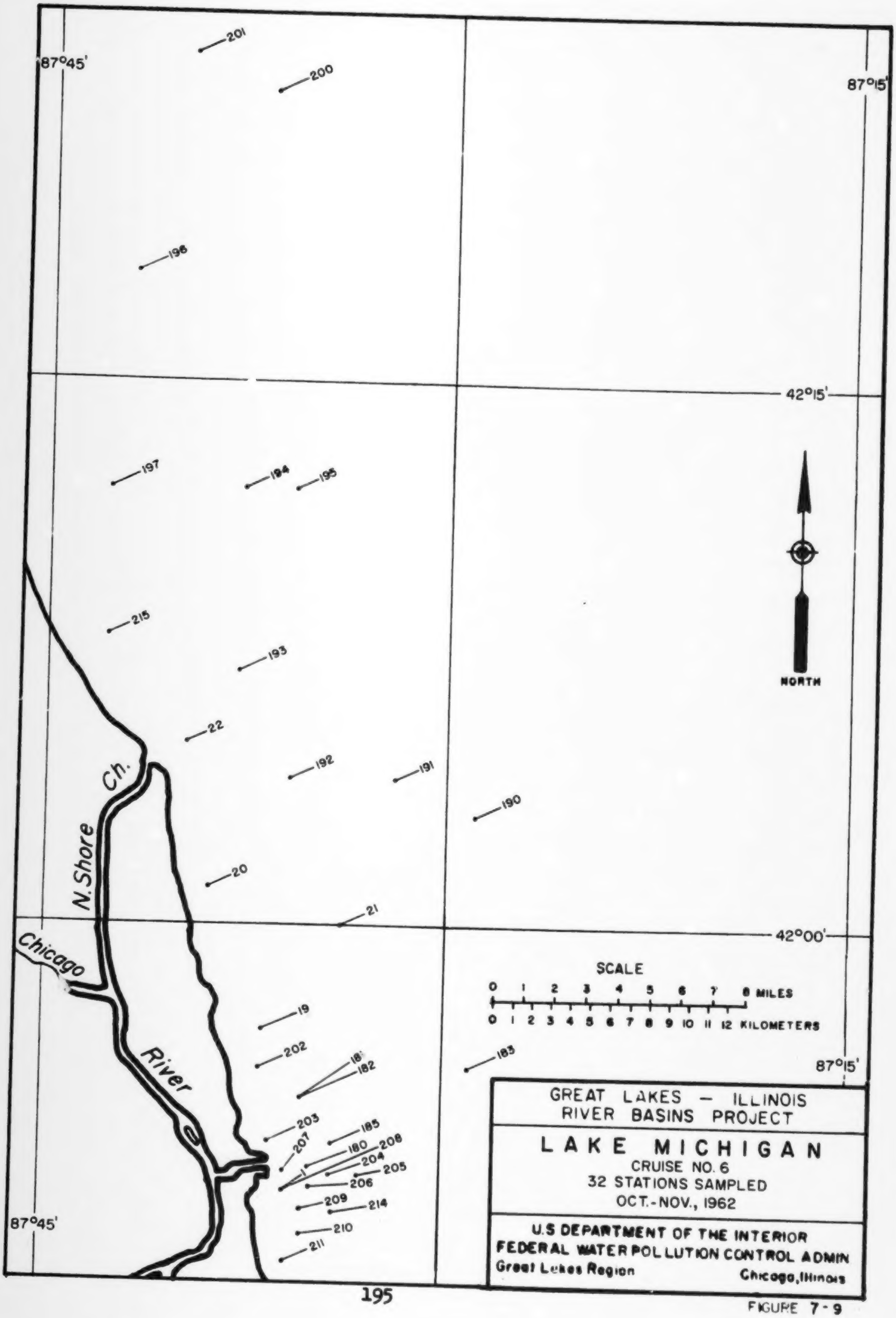

Manitowoc R.
Manitowoc
Sheboygan
Port Washington
Milwaukee R.
MILWAUKEE
Racine
Kenosha
WIS.
ILL.
Waukegan
CHICAGO
Canal
Desplaines R.
S.B.S.
L. Cal. R.
Gary
ILL.
IND.
Michigan City
MICH.
IND.
Manistee
Ludington
Muskegon R.
Muskegon
Grand R.
Grand Haven
Saugatuck
Kalamazoo R.
South Haven
Benton Harbor
St Joseph R.
NORTH
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
88°
87°
86°
44°
43°
42°
30'
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 5
63 STATIONS SAMPLED
OCT, 1962

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-8

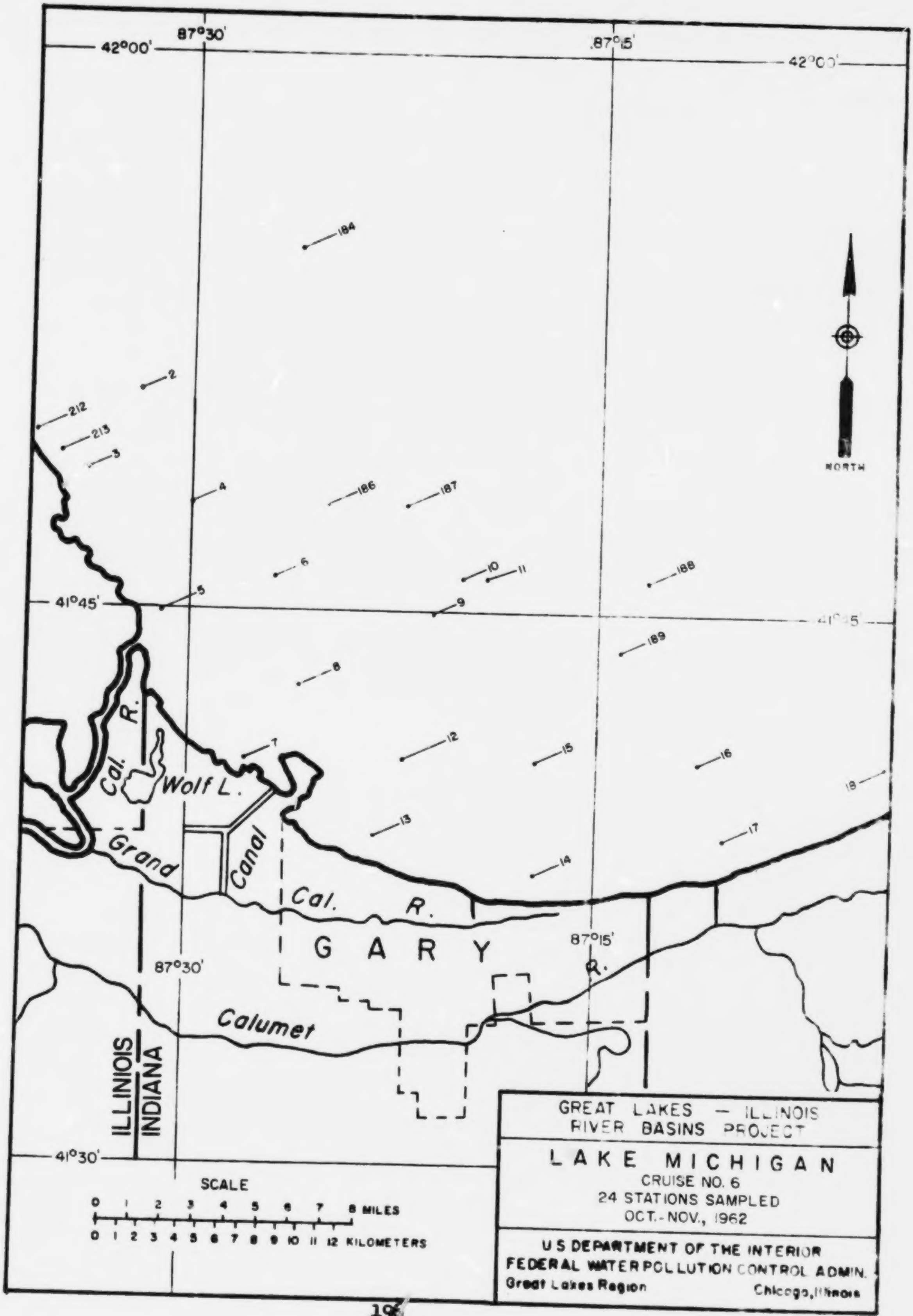

201
200
87°45'
87°15'
196
42°15'
197
194
195
NORTH
215
193
22
192
191
190
N. Shore
Ch.
20
21
42°00'
Chicago
SCALE
0 1 2 3 4 5 6 7 8 MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 KILOMETERS
19
202
181
182
183
87°15'
River
203
207
185
180
208
1
204
205
206
209
214
210
211
87°45'

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 6
32 STATIONS SAMPLED
OCT.-NOV., 1962

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-9

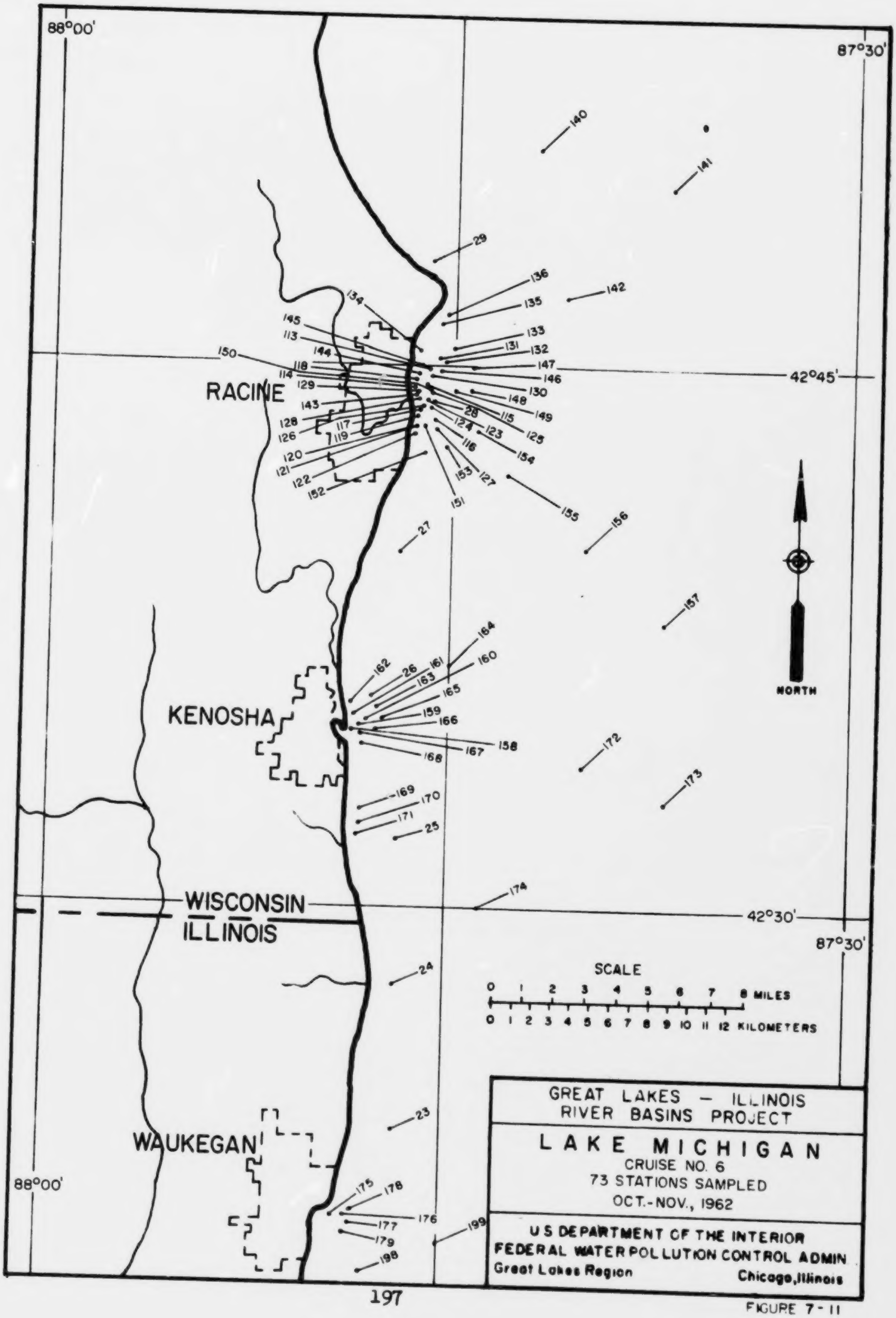

42°00'
87°30'
87°15'
42°00'
184
2
212
213
3
4
186
187
6
10
11
188
5
41°45'
9
41°45'
189
8
Cal.
R.
Wolf L.
7
12
15
16
18
13
17
14
Grand
Canal
Cal.
R.
G A R Y
87°15'
87°30'
R.
Calumet
ILLINOIS
INDIANA
41°30'
NORTH
SCALE
0 1 2 3 4 5 6 7 8 MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 KILOMETERS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 6
24 STATIONS SAMPLED
OCT.-NOV., 1962

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-10

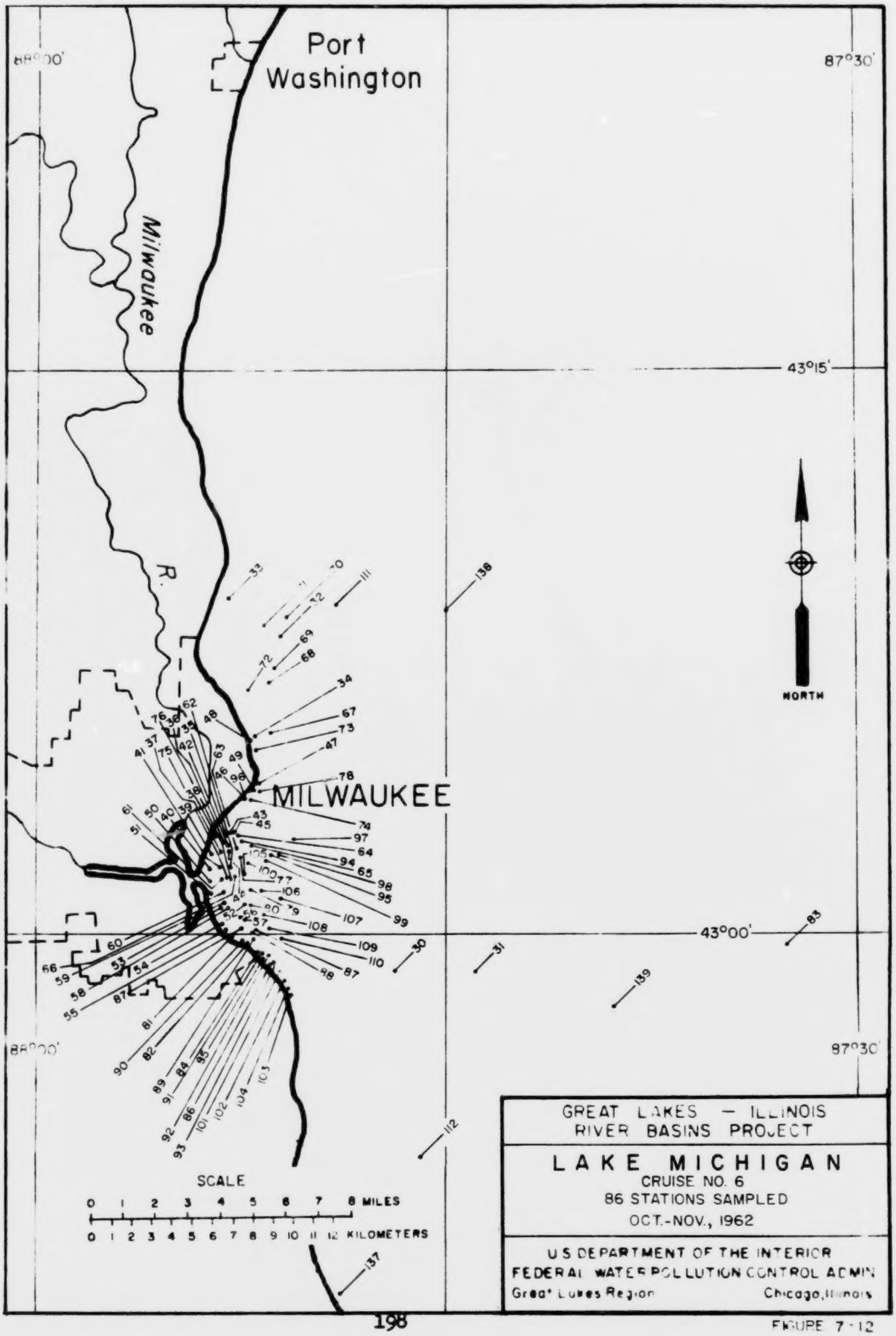

88°00'
87°30'
42°45'
42°30'
88°00'
87°30'
RACINE
KENOSHA
WISCONSIN
ILLINOIS
WAUKEGAN
NORTH
SCALE
0 1 2 3 4 5 6 7 8 MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 KILOMETERS
140
141
29
136
135
142
134
145
113
133
131
132
147
146
150
144
118
114
129
130
148
143
149
28
115
128
117
124
123
125
126
119
120
116
154
121
153
127
122
152
151
155
156
27
157
164
162
26
161
163
160
165
159
166
158
167
168
172
173
169
170
171
25
174
24
23
175
178
176
177
179
199
198

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 6
73 STATIONS SAMPLED
OCT.-NOV., 1962

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region
Chicago, Illinois

FIGURE 7-11

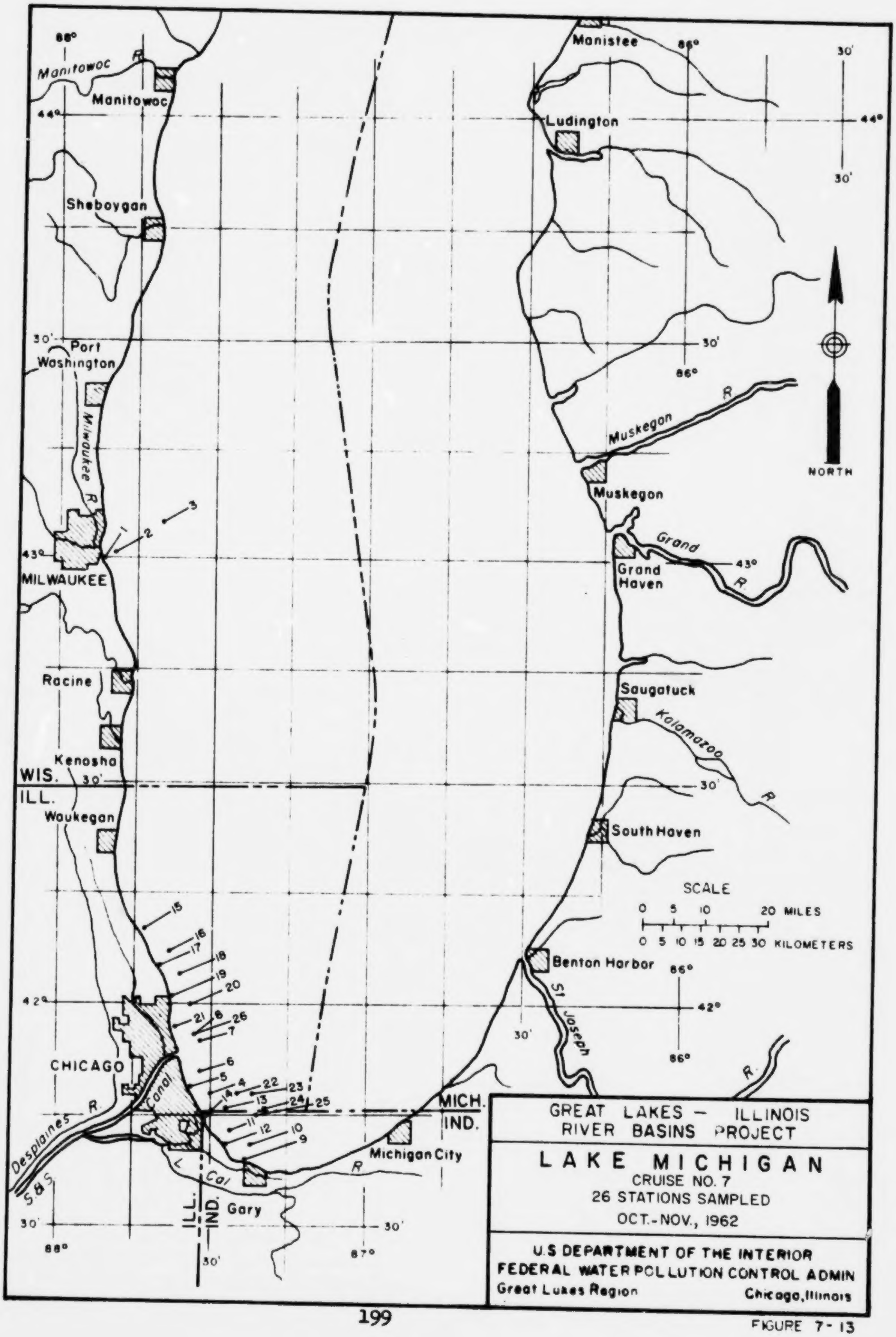

Port Washington
88°00'
87°30'
Milwaukee
R.
43°15'
NORTH
MILWAUKEE
43°00'
88°00'
87°30'
33
70
71
32
111
138
69
72
68
34
67
73
47
48
62
76
36
35
37
42
41
75
63
49
46
96
78
38
39
40
50
61
51
43
45
74
97
64
94
65
98
95
105
100
77
106
80
79
107
99
108
57
109
110
30
31
83
139
88
87
60
66
59
53
54
58
55
81
82
90
89
84
85
91
86
92
101
102
104
103
93
112
137
SCALE
0 1 2 3 4 5 6 7 8 MILES
0 1 2 3 4 5 6 7 8 9 10 11 12 KILOMETERS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 6
86 STATIONS SAMPLED
OCT.-NOV., 1962

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-12

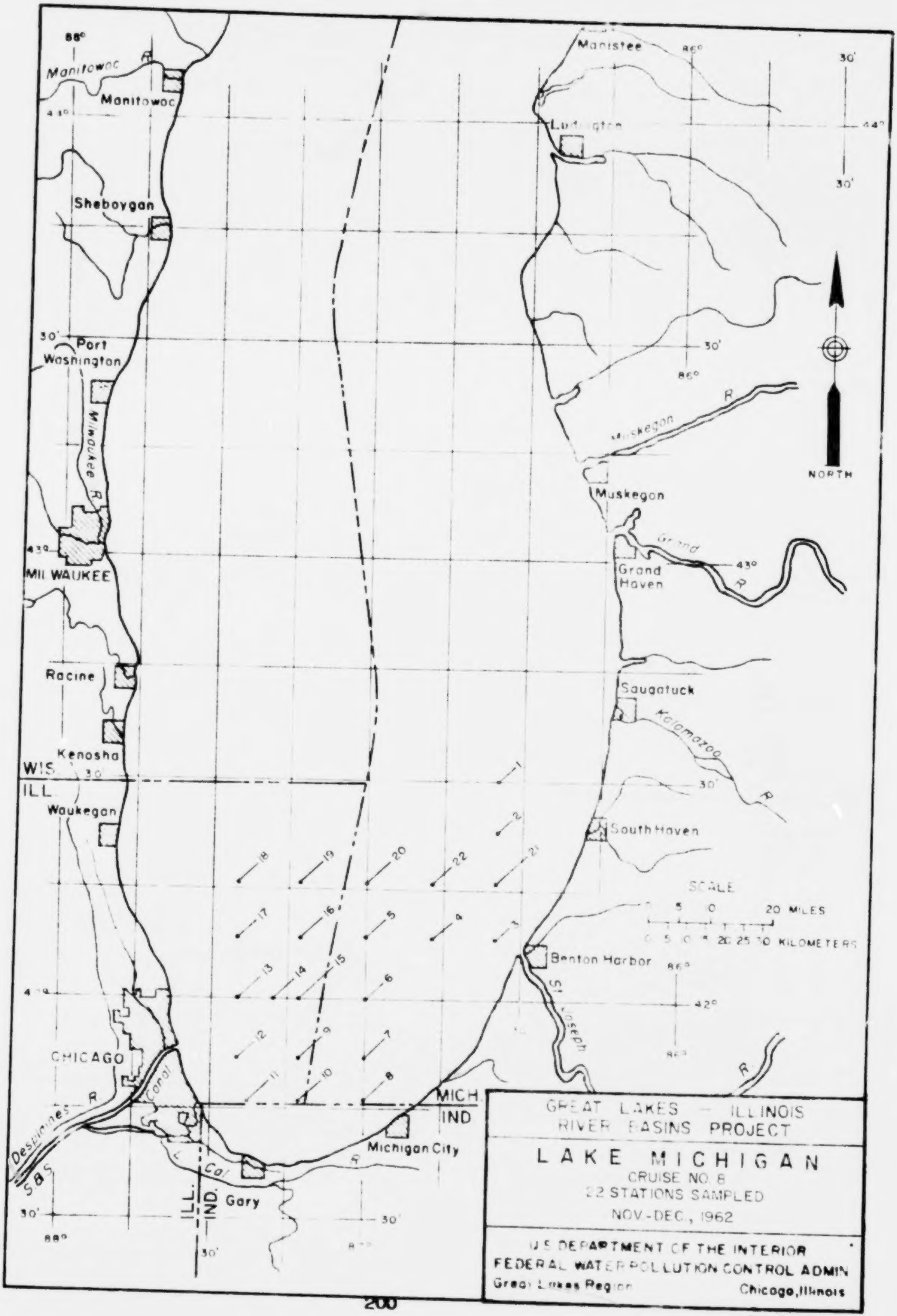

88°
Manitowoc R.
Manitowoc
44°
Sheboygan
30'
Port Washington
Milwaukee R.
43°
MILWAUKEE
1
2
3
Racine
Kenosha
WIS.
ILL.
30'
Waukegan
15
16
17
18
19
20
42°
21
8
26
7
6
5
4
22
23
14
13
24
25
11
12
10
9
CHICAGO
Canal
Desplaines R.
S.&S.
L. Cal. R.
Gary
ILL.
IND.
MICH.
IND.
Michigan City
30'
88°
30'
87°
30'
Manistee
86°
30'
Ludington
44°
30'
30'
86°
Muskegon R.
Muskegon
NORTH
Grand R.
43°
Grand Haven
Saugatuck
Kalamazoo R.
30'
South Haven
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
Benton Harbor
86°
42°
86°
St Joseph R.
R.
30'

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 7
26 STATIONS SAMPLED
OCT.-NOV., 1962

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7- 13

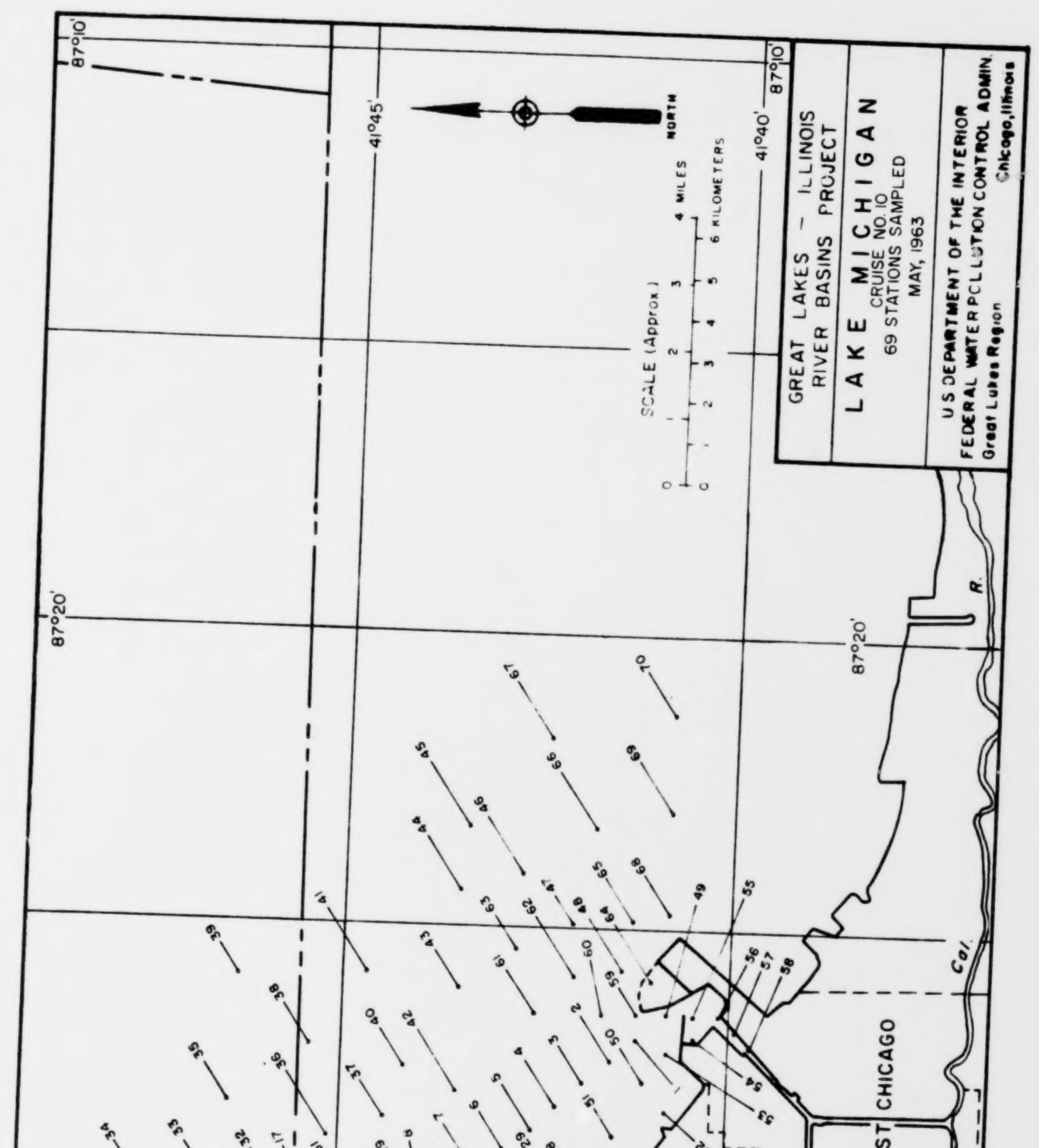

88°
Manitowoc R
Manitowoc
43°
Sheboygan
30'
Port Washington
Milwaukee R
43°
MILWAUKEE
Racine
Kenosha
WIS.
ILL.
30'
Waukegan
42°
CHICAGO
R
Canal
Desplaines
SBS
L. Cal R
Gary
ILL.
IND.
30'
88°
30'
87°
30'
MICH.
IND.
Michigan City
Manistee
86°
30'
Ludington
44°
30'
30'
86°
Muskegon R
Muskegon
NORTH
Grand R
43°
Grand Haven
Saugatuck
Kalamazoo R
30'
South Haven
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
Benton Harbor
86°
42°
St. Joseph
86°
R
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 8
22 STATIONS SAMPLED
NOV.-DEC., 1962

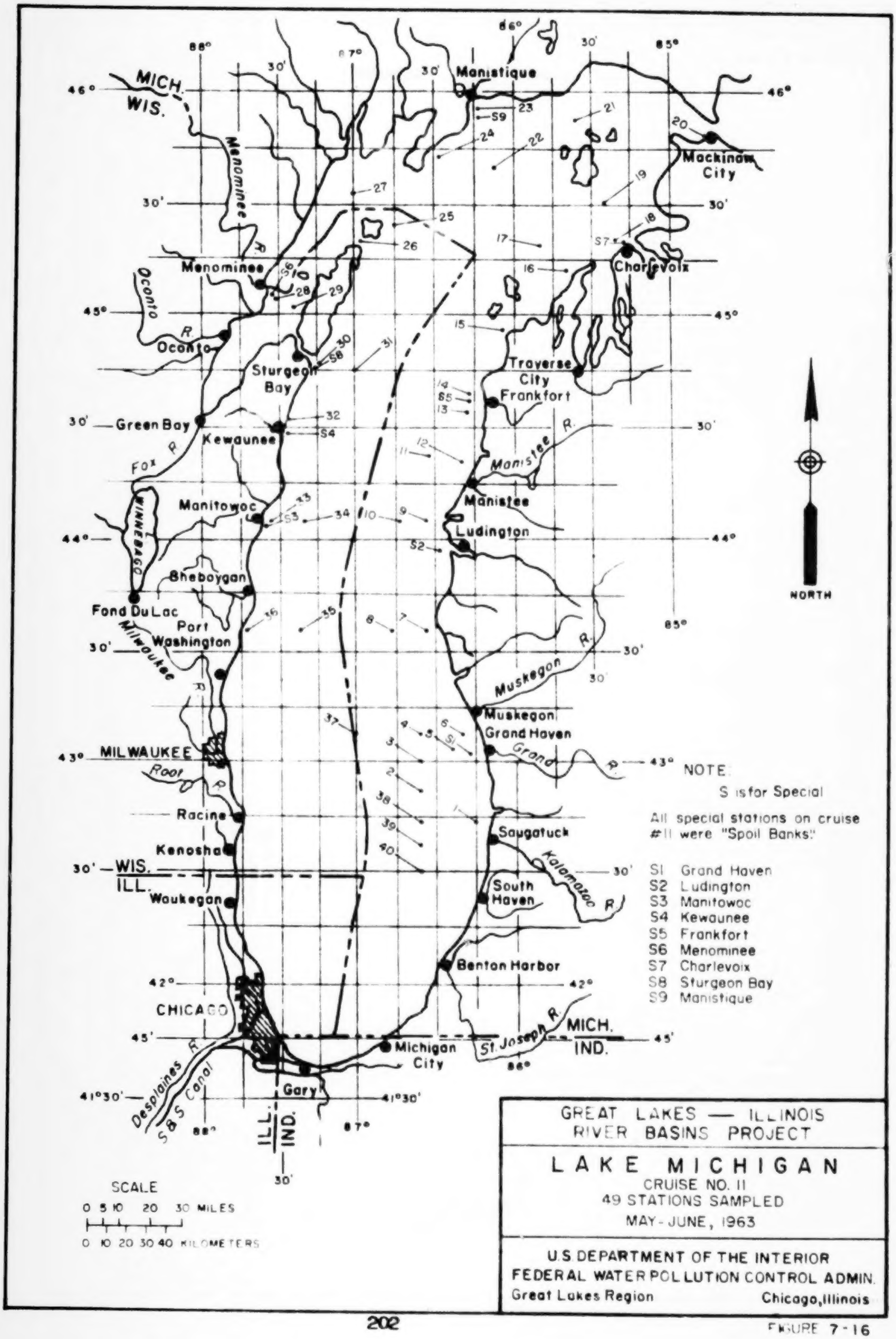
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-14


GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT
LAKE MICHIGAN
CRUISE NO.10
69 STATIONS SAMPLED
MAY, 1963
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois
SCALE (Approx.)
0 1 2 3 4 MILES
0 1 2 3 4 5 6 KILOMETERS
NORTH
87°10'
87°20'
87°30'
41°45'
41°40'
EAST CHICAGO
Whiting
LAKE CO.
COOK CO.
IND.
ILL.
Wolf L.
Cal. R.
Grand Cal. R.

201

FIGURE 7-15


MICH.
WIS.
Manistique
Mackinaw City
Charlevoix
Menominee
Oconto
Sturgeon Bay
Green Bay
Kewaunee
Traverse City
Frankfort
Manistee
Manitowoc
Ludington
Sheboygan
Fond Du Lac
Port Washington
Muskegon
Grand Haven
MILWAUKEE
Racine
Kenosha
Saugatuck
WIS.
ILL.
Waukegan
South Haven
Benton Harbor
CHICAGO
Michigan City
MICH.
IND.
Gary
ILL.
IND.
Menominee R.
Oconto R.
Fox R.
WINNEBAGO
Milwaukee
Root R.
Manistee R.
Muskegon R.
Grand R.
Kalamazoo R.
St. Joseph R.
Desplaines R.
S&S Canal
NORTH
88°
87°
86°
85°
46°
45°
44°
43°
42°
41°30'
30'
45'
SCALE
0 5 10 20 30 MILES
0 10 20 30 40 KILOMETERS

NOTE:
S is for Special
All special stations on cruise #11 were "Spoil Banks."

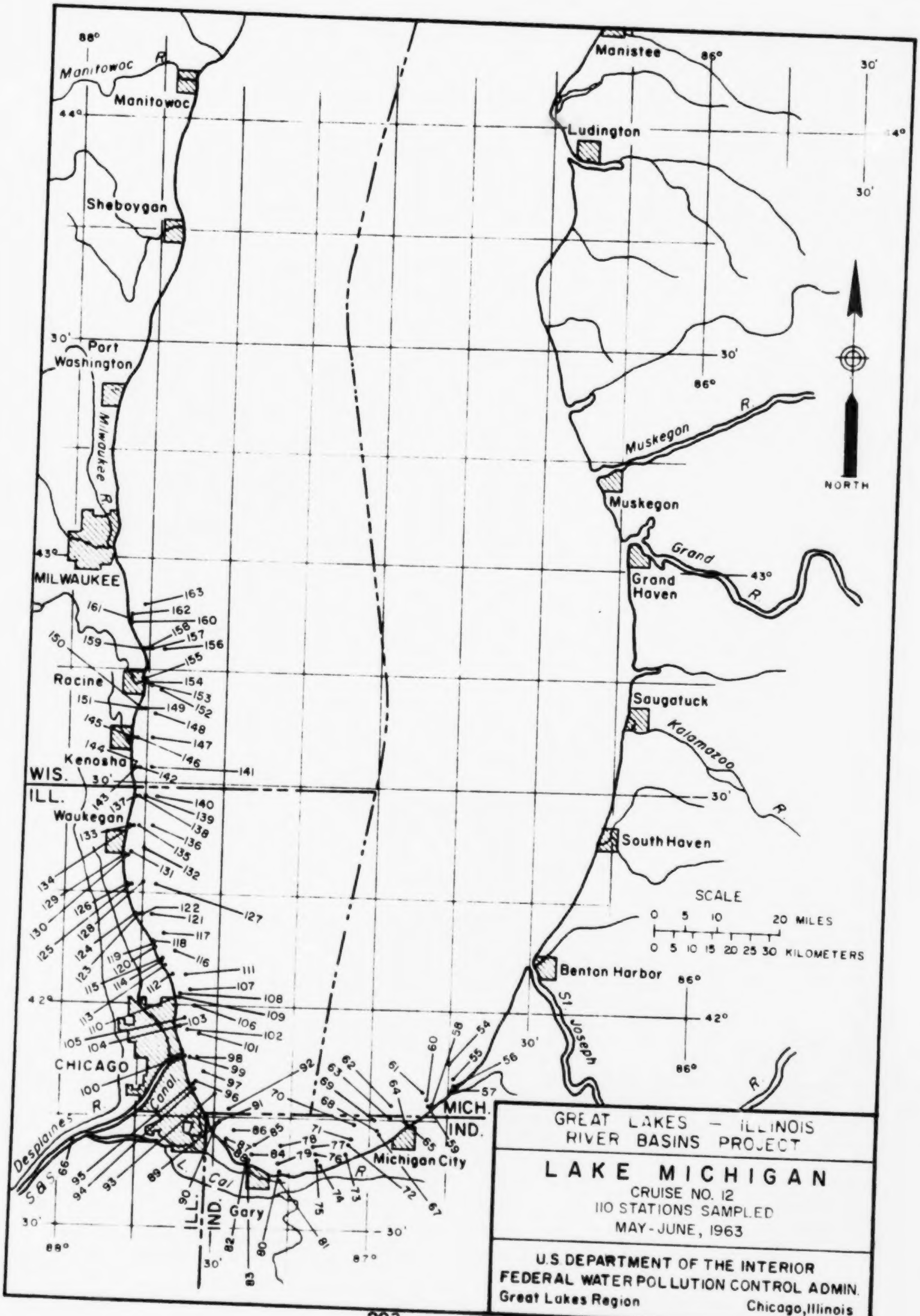
S1	Grand Haven
S2	Ludington
S3	Manitowoc
S4	Kewaunee
S5	Frankfort
S6	Menominee
S7	Charlevoix
S8	Sturgeon Bay
S9	Manistique

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 11
49 STATIONS SAMPLED
MAY-JUNE, 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-16



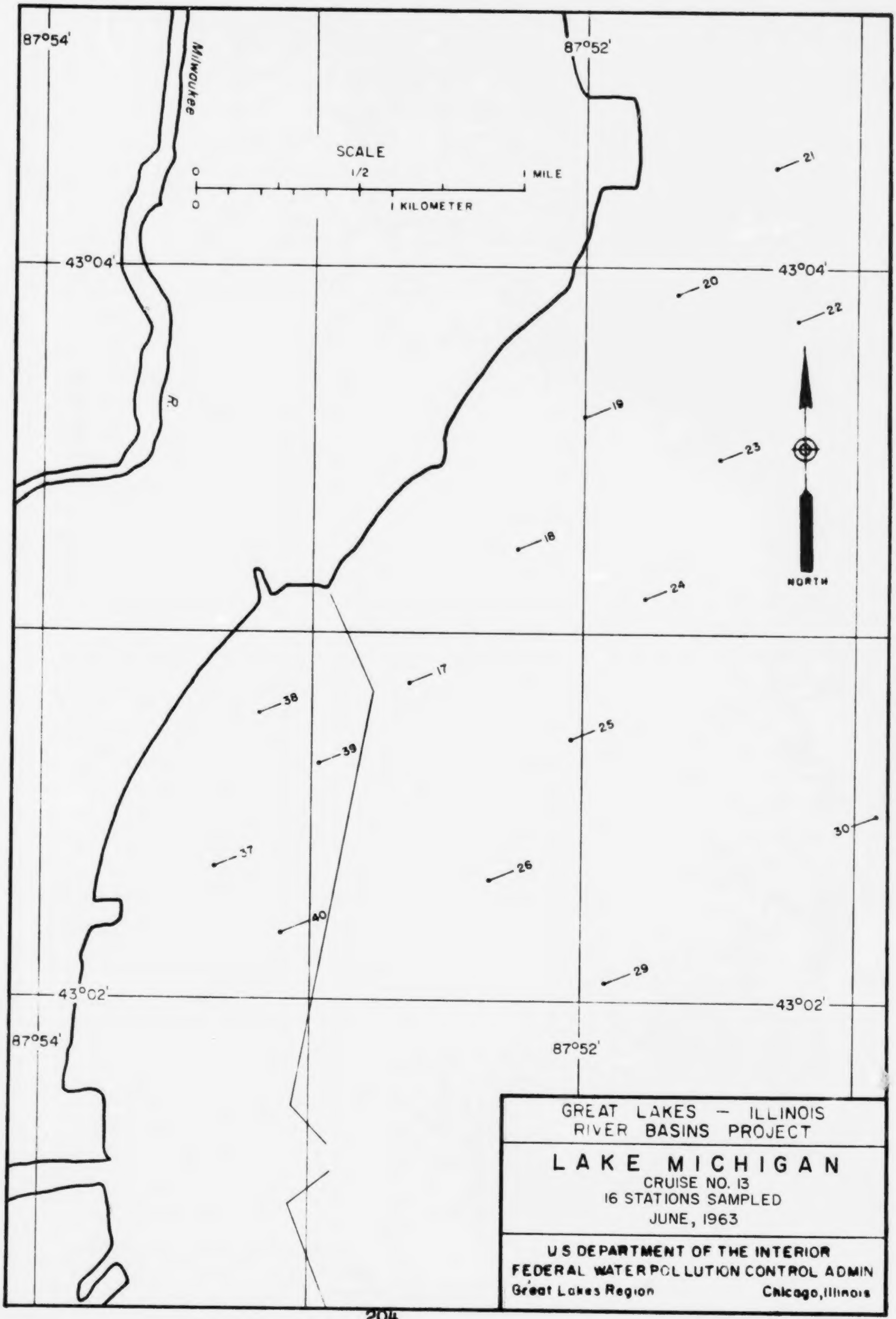
88°
Manitowoc R
Manitowoc
44°
Sheboygan
30'
Port Washington
Milwaukee R
43°
MILWAUKEE
Racine
Kenosha
WIS.
ILL.
Waukegan
42°
CHICAGO
Canal
Desplaines R
S & S
L. Cal R
Gary
ILL.
IND.
30'
88°
87°
Manistee
86°
30'
Ludington
44°
30'
30'
86°
Muskegon R
Muskegon
NORTH
Grand R
Grand Haven
43°
Saugatuck
Kalamazoo R
30'
South Haven
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
Benton Harbor
86°
St Joseph
42°
86°
R
MICH.
IND.
Michigan City
163
162
161
160
158
157
156
159
150
155
154
153
152
151
149
148
145
147
144
146
141
142
143
137
140
139
138
133
136
135
132
134
131
129
127
122
121
126
130
128
117
125
124
118
123
119
116
120
114
115
111
112
107
108
109
113
110
103
106
105
104
102
101
98
99
100
97
96
92
91
63
62
69
68
70
61
64
60
58
54
55
56
57
59
65
71
77
78
76
79
72
73
74
75
67
86
85
87
84
89
88
66
95
94
93
89
90
82
83
80
81

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 12
110 STATIONS SAMPLED
MAY-JUNE, 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-17

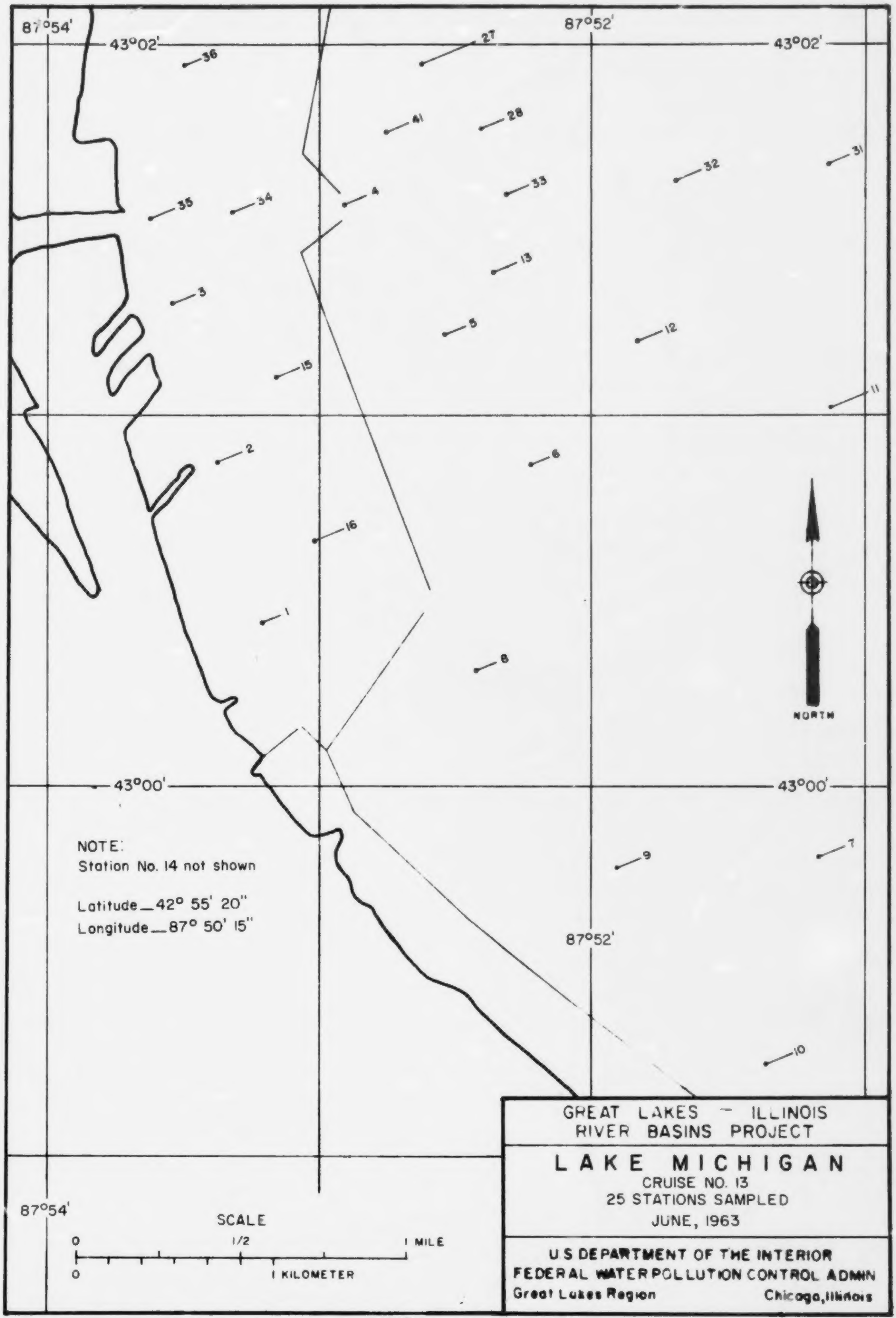

87°54'
87°52'
Milwaukee
R.
SCALE
0
1/2
1 MILE
0
1 KILOMETER
43°04'
43°04'
43°02'
43°02'
87°54'
87°52'
NORTH
21
20
22
19
23
18
24
17
38
25
39
30
37
26
40
29

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 13
16 STATIONS SAMPLED
JUNE, 1963

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-18



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 13
25 STATIONS SAMPLED
JUNE, 1963

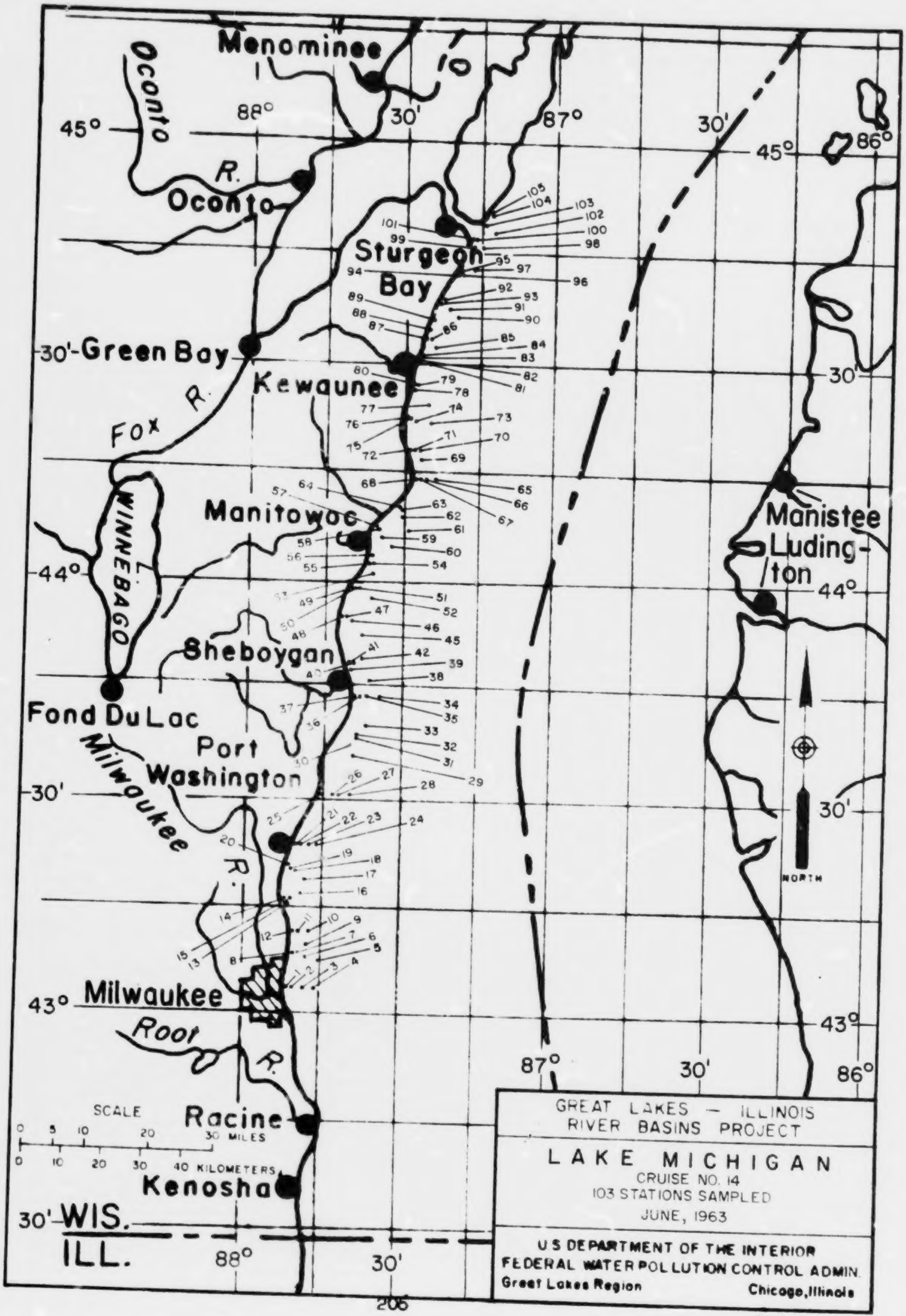
U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

NOTE:
Station No. 14 not shown

Latitude — 42° 55' 20"
Longitude — 87° 50' 15"

87°54'
43°02'
87°52'
43°02'
36
27
41
28
31
32
33
35
34
4
13
3
5
12
15
11
2
6
16
1
8
NORTH
43°00'
43°00'
9
7
87°52'
10
87°54'
SCALE
0
1/2
1 MILE
0
1 KILOMETER

FIGURE 7-19

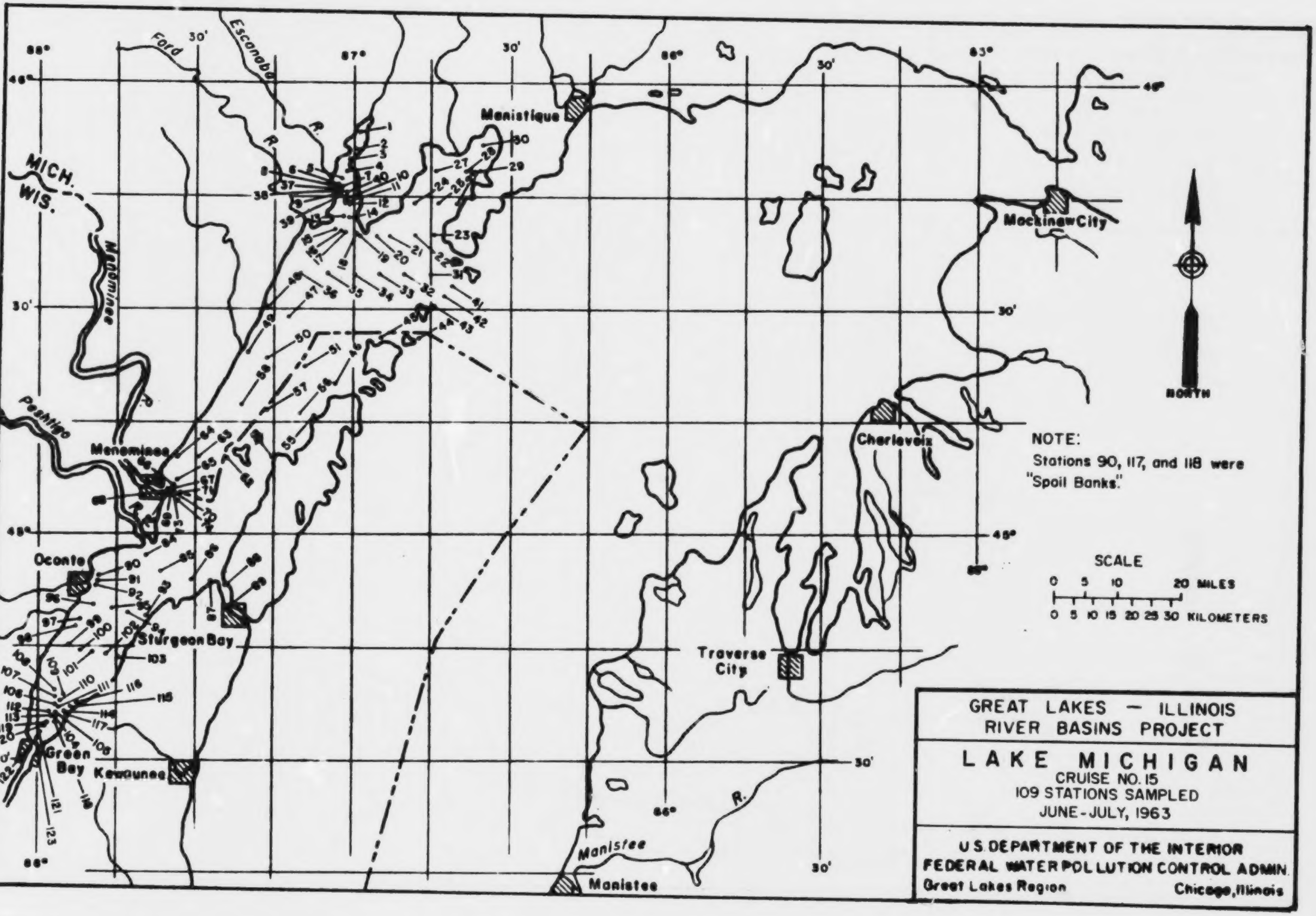

Menominee
Oconto
R.
Oconto
Sturgeon Bay
Green Bay
Kewaunee
Fox R.
Winnebago
Manitowoc
Sheboygan
Fond Du Lac
Port Washington
Milwaukee R.
Milwaukee
Root R.
Racine
Kenosha
WIS.
ILL.
Manistee
Ludington
NORTH
45°
44°
43°
30'
88°
87°
86°
SCALE
0 5 10 20 30 MILES
0 10 20 30 40 KILOMETERS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 14
103 STATIONS SAMPLED
JUNE, 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-20


88°
30'
87°
30'
86°
30'
85°
46°
30'
45°
MICH.
WIS.
Ford
Escanaba
R.
R.
Menominee
R.
Peshtigo
Manistique
Mackinaw City
Charlevoix
Traverse City
Menominee
Oconto
Sturgeon Bay
Green Bay
Kewaunee
Manistee
Manistee
R.
NORTH
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS

NOTE:
Stations 90, 117, and 118 were "Spoil Banks."

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN
CRUISE NO. 15
109 STATIONS SAMPLED
JUNE-JULY, 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-21

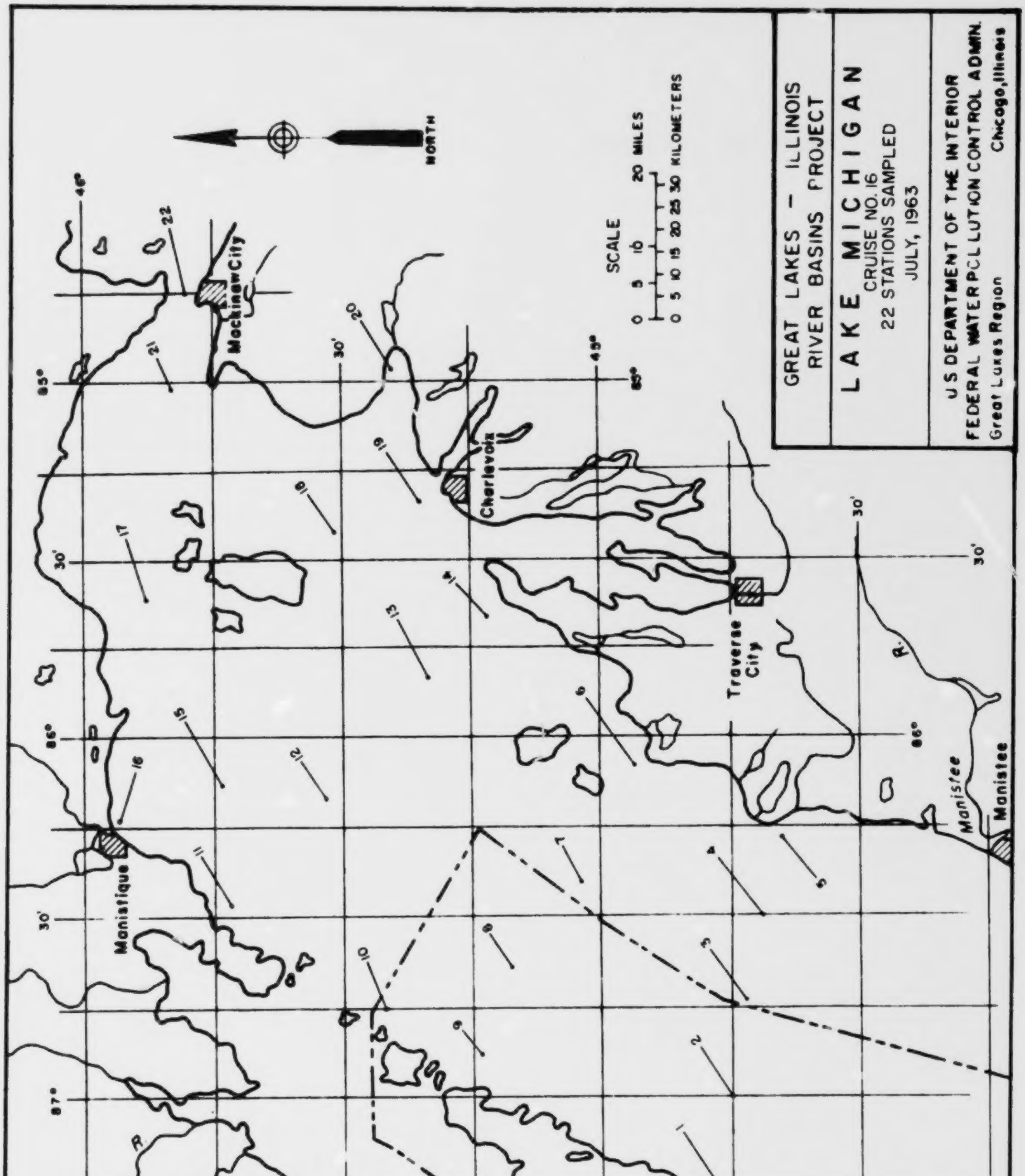

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT
LAKE MICHIGAN
CRUISE NO. 16
22 STATIONS SAMPLED
JULY, 1963
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois
SCALE
0 5 10 20 MILES
0 5 10 15 20 25 30 KILOMETERS
NORTH
Mackinaw City
Charlevoix
Traverse City
Manistee
Manistee R.
Manistique
Escanaba R.
Ford R.
Menominee R.
Menominee
Peshtigo R.
Oconto
Sturgeon Bay
Kewaunee
Green Bay
MICH.
WIS.
46°
45°
30'
85°
86°
87°
88°
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

FIGURE 7-22

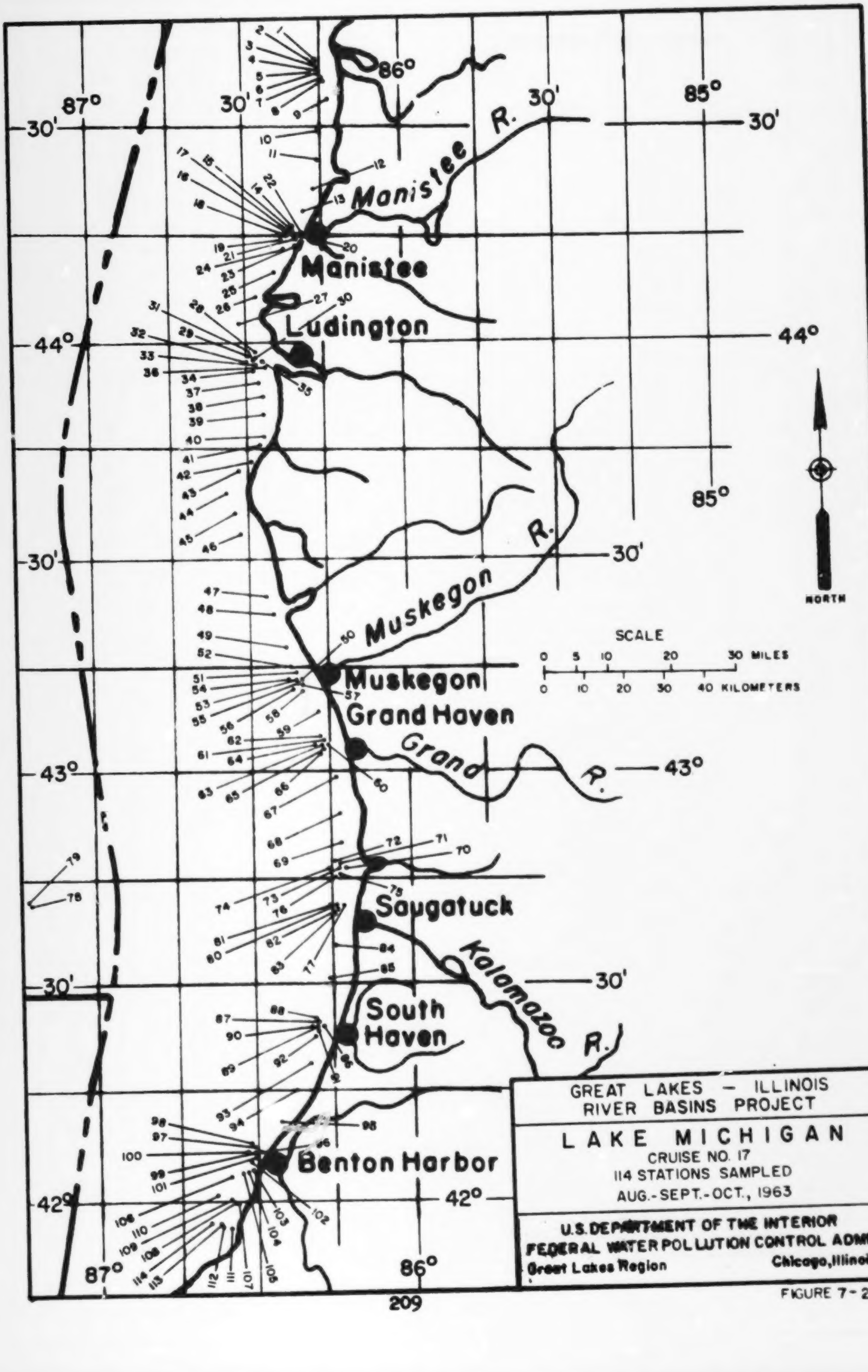

86°
30'
87°
85°
30'
Manistee R.
Manistee
Ludington
44°
Muskegon R.
Muskegon
Grand Haven
Grand R.
43°
Saugatuck
Kalamazoo R.
South Haven
Benton Harbor
42°
87°
86°
85°
NORTH
SCALE
0 5 10 20 30 MILES
0 10 20 30 40 KILOMETERS
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT
LAKE MICHIGAN
CRUISE NO. 17
114 STATIONS SAMPLED
AUG.-SEPT.-OCT., 1963
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois

FIGURE 7-23

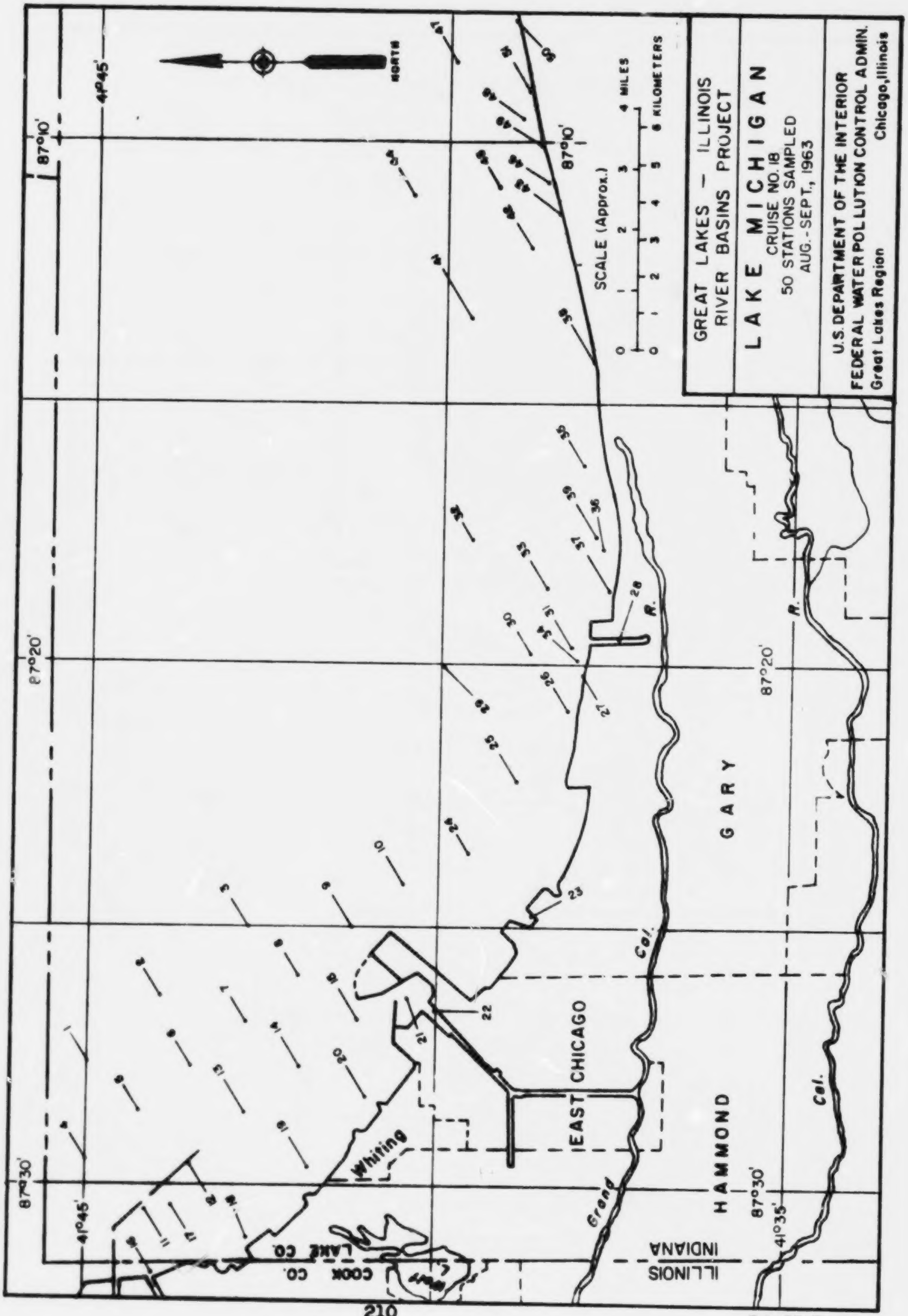
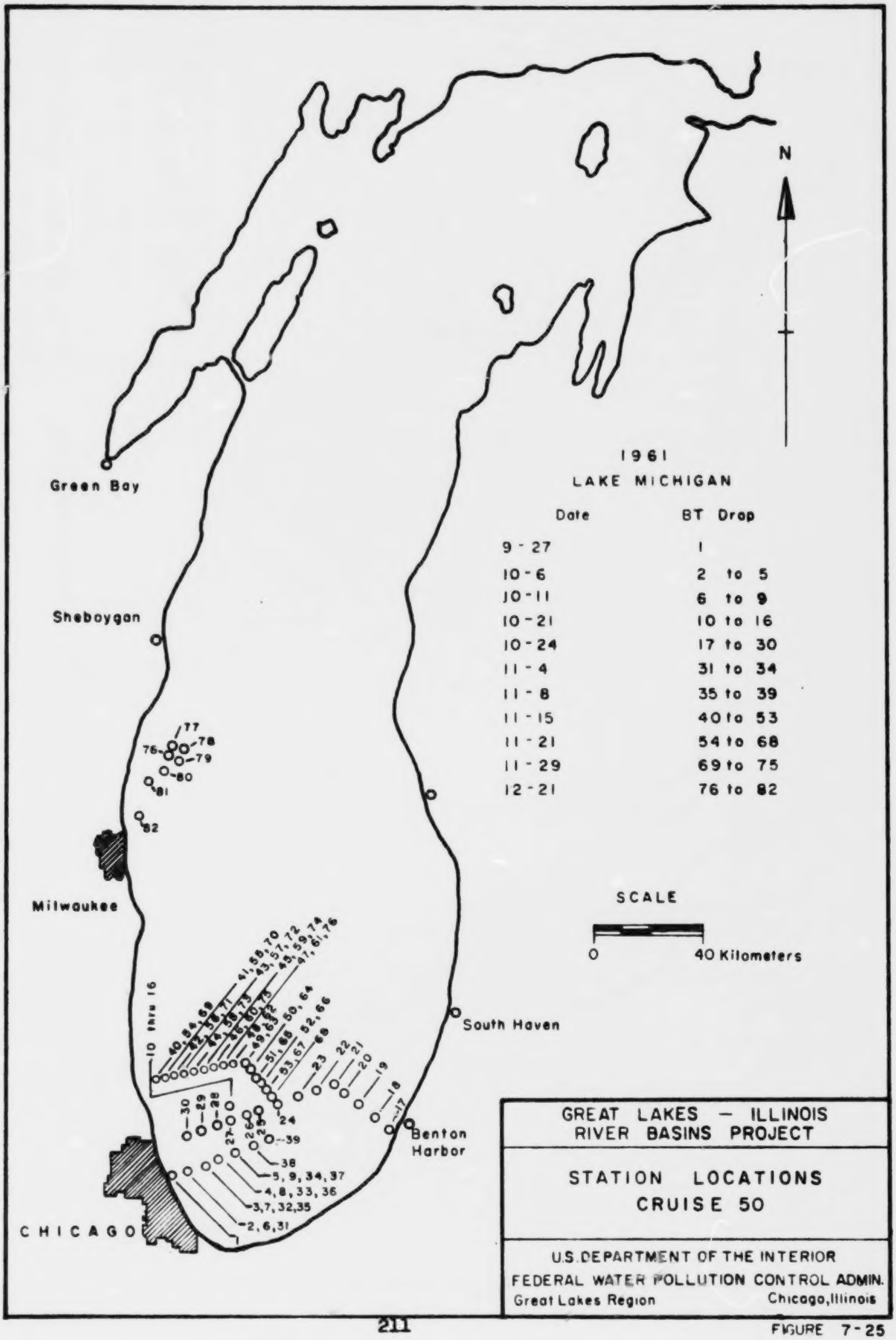

GREAT LAKES – ILLINOIS RIVER BASINS PROJECT
LAKE MICHIGAN
CRUISE NO. 18
50 STATIONS SAMPLED
AUG.-SEPT., 1963
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois
SCALE (Approx.)
4 MILES
8 KILOMETERS
NORTH
87°10'
87°20'
87°30'
41°45'
41°35'
GARY
EAST CHICAGO
HAMMOND
Whiting
ILLINOIS
INDIANA
COOK CO.
LAKE CO.
Grand
Cal.
R.

FIGURE 7-24


N
Green Bay
Sheboygan
Milwaukee
CHICAGO
South Haven
Benton Harbor
77
78
76
79
80
81
82
10 thru 16
40, 54, 69
42, 56, 71
44, 58, 73
46, 60, 75
48, 62
49, 63
41, 55, 70
43, 57, 72
45, 59, 74
47, 61, 76
50, 64
51, 65
52, 66
53, 67
68
23
22
21
20
19
18
17
30
29
28
27
26
25
24
39
38
5, 9, 34, 37
4, 8, 33, 36
3, 7, 32, 35
2, 6, 31
1
SCALE
0
40 Kilometers

1961
LAKE MICHIGAN

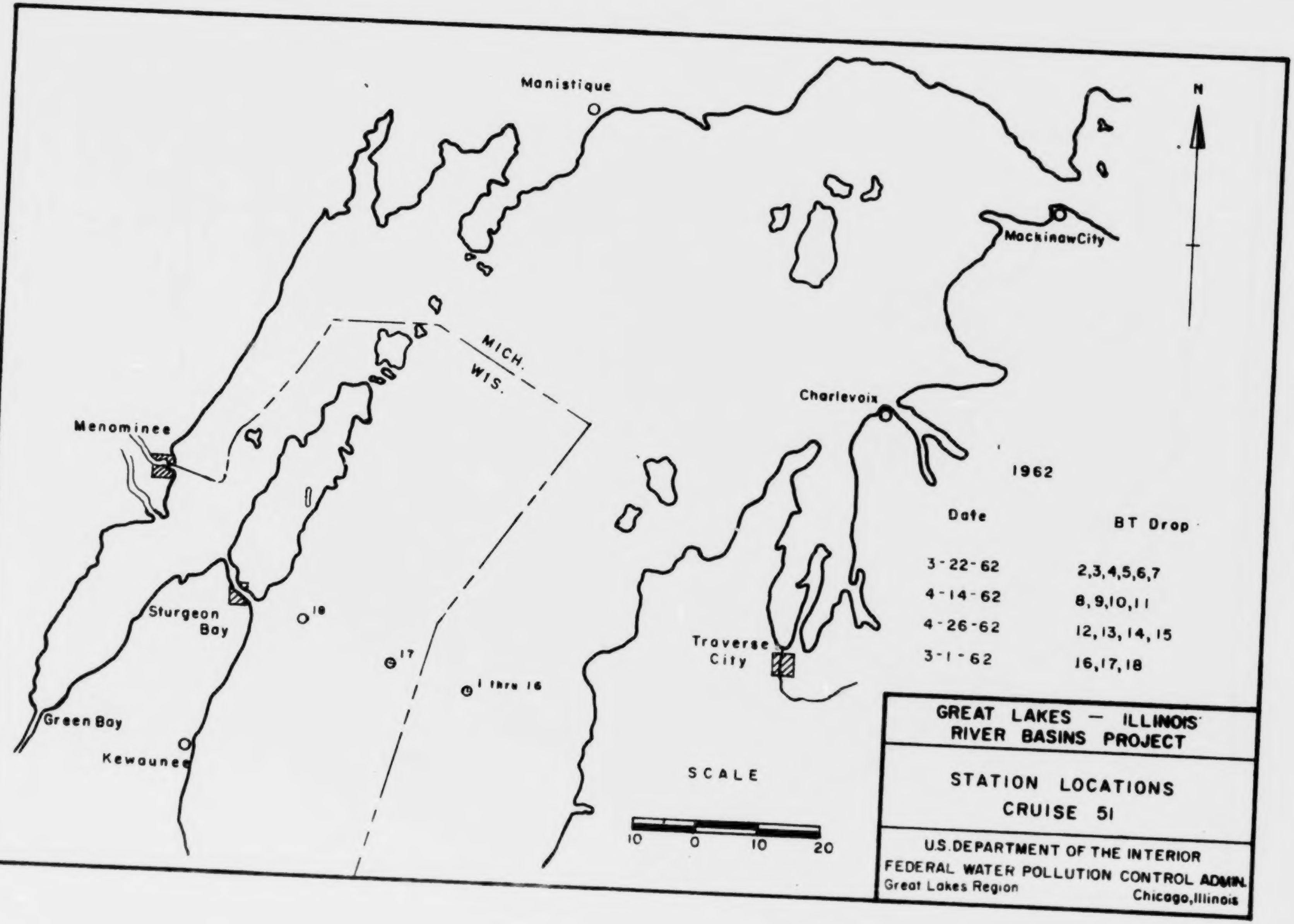
Date	BT Drop
9 - 27	1
10 - 6	2 to 5
10 - 11	6 to 9
10 - 21	10 to 16
10 - 24	17 to 30
11 - 4	31 to 34
11 - 8	35 to 39
11 - 15	40 to 53
11 - 21	54 to 68
11 - 29	69 to 75
12 - 21	76 to 82

GREAT LAKES – ILLINOIS RIVER BASINS PROJECT

STATION LOCATIONS
CRUISE 50

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-25



N
Manistique
Mackinaw City
Charlevoix
Traverse City
MICH.
WIS.
Menominee
Sturgeon Bay
Green Bay
Kewaunee
18
17
1 thru 16
SCALE
10
0
10
20

1962

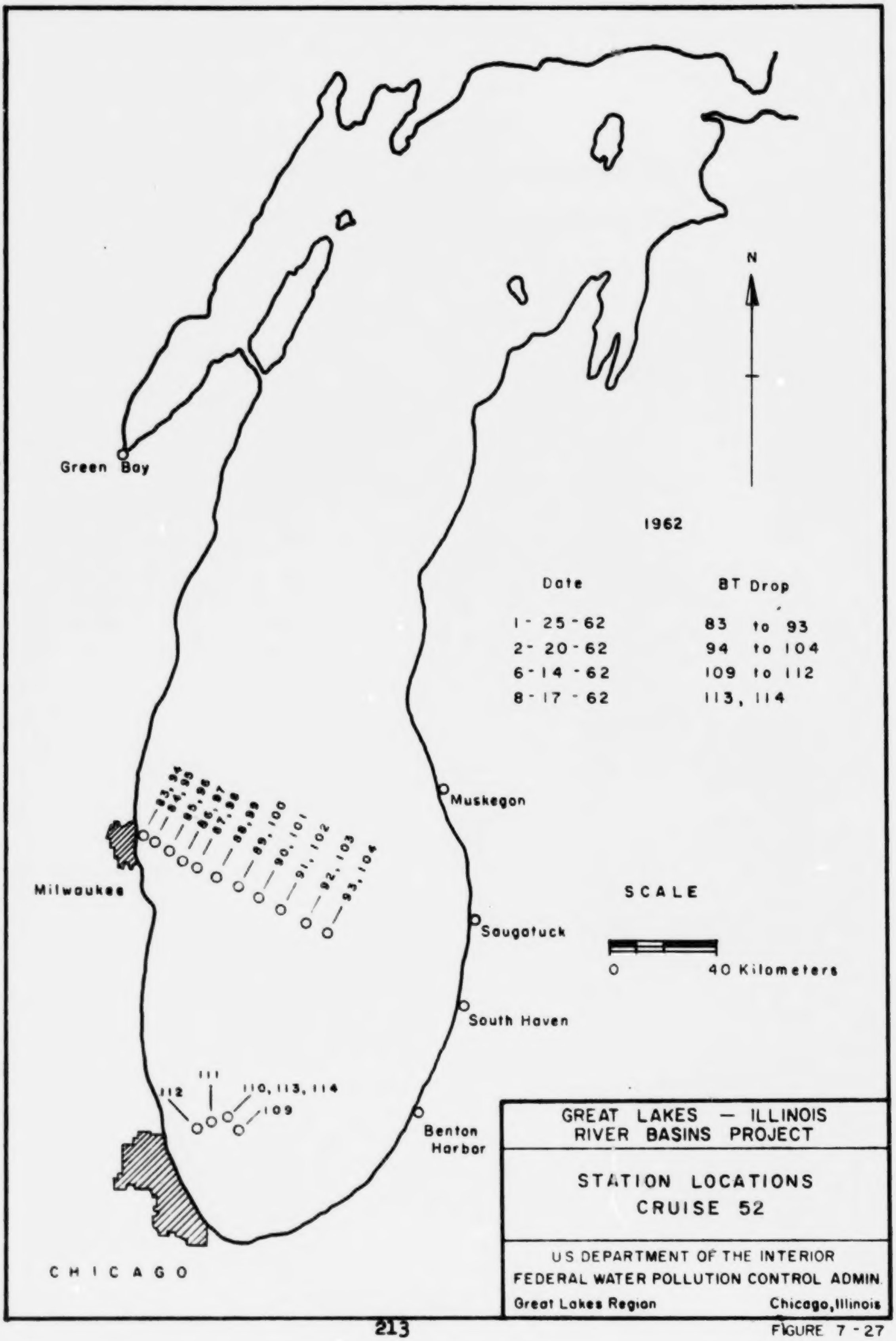
Date	BT Drop
3-22-62	2,3,4,5,6,7
4-14-62	8,9,10,11
4-26-62	12,13,14,15
3-1-62	16,17,18

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STATION LOCATIONS
CRUISE 51

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois

FIGURE 7-26


N
Green Bay
Muskegon
Milwaukee
Saugatuck
South Haven
Benton Harbor
CHICAGO
SCALE
0
40 Kilometers
83, 94
84, 95
85, 96
86, 97
87, 98
88, 99
89, 100
90, 101
91, 102
92, 103
93, 104
112
111
110, 113, 114
109

1962

Date	BT Drop
1-25-62	83 to 93
2-20-62	94 to 104
6-14-62	109 to 112
8-17-62	113, 114

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STATION LOCATIONS
CRUISE 52

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-27

TABLE 7-2

TEMPERATURE DATA AND STATION LOCATION

CRUISE 001 YEAR 1962

DEPTH		STATION NUMBERS	
FEET	METERS	002 (Temp., °C)	003
000	000	03.5	06.5
010	003	03.5	06.5
020	006	03.5	06.5
030	009	03.5	06.5
040	012	03.5	06.5
050	015	03.4	06.5
060	018	03.4	06.5
070	021	03.4	06.5
080	024	03.4	
090	028	03.4	
100	031	03.4	
120	037	03.4	
140	043	03.4	
160	049	03.4	
180	055	03.4	
200	061		
300	092		
400	122		
500	153		
600	183		
700	214		
800	244		

TIME	1347	0917
DATE	0424	0425
SURFACE TEMP.	03	06
TOTAL DEPTH	195	070
AVERAGE TEMP.	3.4	6.5

TABLE 7-2 (Continued)

TEMPERATURE DATA AND STATION LOCATION

CRUISE	STATION	LATITUDE	LONGITUDE
001	001	424400	861500
001	002	422300	863500
001	003	420000	863800
001	004	420100	865920
001	005	414600	870000
001	006	414600	872000
001	007	420000	871900
001	008	422300	872500
001	009	422300	870000
001	010	424400	872300
001	011	424400	870000
001	012	424400	863500
001	013	430800	870000
001	014	430800	872500
001	015	433600	874400
001	016	433600	872200
001	017	440500	873400
001	018	440500	872000
001	019	440500	870000
001	020	443200	872700
001	021	442800	870000
001	022	444500	870000
001	023	444700	871400
001	024	444300	864400
001	025	444100	863000
001	026	443900	861700
001	027	442500	864000
001	028	442300	863200
001	029	443450	861840
001	030	442100	862000
001	031	440500	863300
001	032	440500	864400
001	033	433600	863300
001	034	430800	863500
001	035	430800	861900
001	036	430300	862410

TABLE 7-3

SCHEDULE OF CRUISES

CRUISE	STATIONS SAMPLED	VESSEL	DATES	OPERATING AREA*
50		PHS-19'	9/27/61, 10/6/61	1
"		USCG-26'	10/11/61	1
"		USCG-Woodbine	10/21/61	1
"		USCG-40'	10/24/61, 11/3/61, 11/8/61, 11/15/61, 11/21/61	1
"		USCG-36'	11/29/61	1
"	106	USCG-64'	12/21/61	2
51	17	R/V Kaho, USCG-Mesquite	3/1/62, 3/20-22/62 4/14/62, 4/26/62	2
52	18	USCG-64'	1/25/62, 2/20/62, 8/17/62, 6/14/62	1
1	36	R/V Cisco	4/24-5/7/62	1, 3
2	29	R/V Cisco	6/5-18/62	2, 3
3	31	R/V Cisco	7/17-30/62	1, 3
4	69	R/V Cisco	8/29-9/9/62	1, 3
5	63	R/V Cisco	10/10-22/62	1
6	215	R/V Fitzgerald	10/18-11/30/62	1, 3
7	26	R/V Kaho	10/28-11/7/62	1
8	22	R/V Kaho	11/28-12/6/62	1
9		THIS NUMBER NOT USED		
10	70	T-509	5/8-23/63	3
11	40	R/V Cisco	5/23-6/3/63	2, 3
12	109	T-509	5/22-6/9/63	3
13	41	T-509	6/9-6/12/63	3
14	105	T-509	6/13-6/25/63	3
15	123	T-509	6/26-7/12/63	2
16	22	T-509	7/15-7/26/63	2
17	114	T-509 Intermittent	8/8/63-10/8/63	1, 3
18	51	T-509	8/20-9/19/63	3

*1 South Basin
2 North Basin
3 Shore or Harbor

meters to the bottom the data were read at 30-meter intervals. The date, time, surface temperature (using a hand thermometer), and total depth were recorded. On many cruises two or more BT casts were made at the station. In general, a cast was made prior to sampling the station and after all sampling was completed.

Temperature Recorder Data

Temperature recorder data were collected at all current meter stations in Lake Michigan, Figure 7-28. Approximately 2 million hours of data have been collected. The purpose of the recorders was to ascertain the relative position of the thermocline with respect to the current meter.

Results - BT Surveys

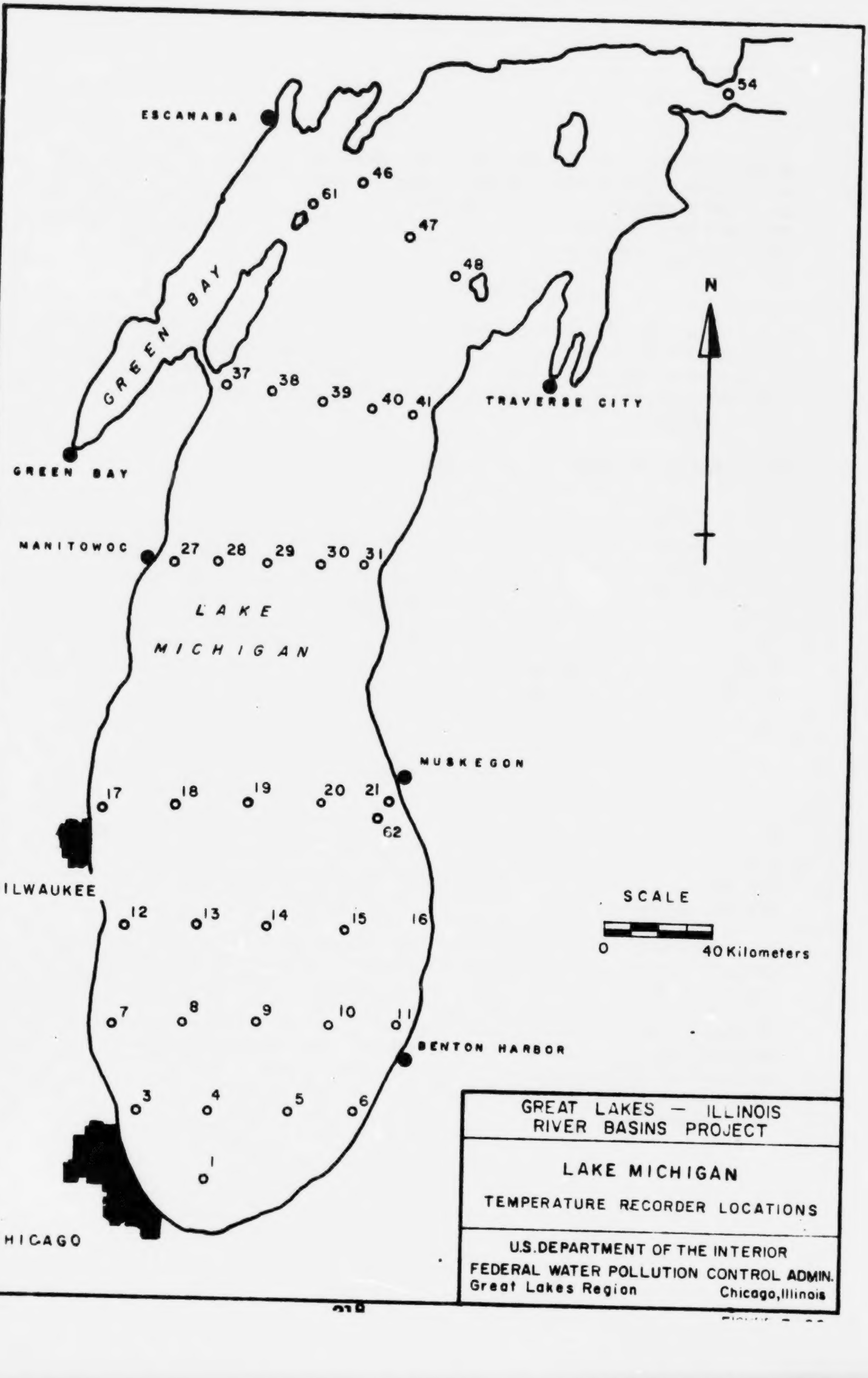
Fall, 1961

Studies during the fall of 1961 were made only in the southern basin. This period includes data from the latter part of September through December. The inshore areas with depths to 20 meters were nearly isothermal, with surface temperatures of 15.5°C and still 15.0°C at 20 meters. The thermocline appeared sharply defined at depths up to 24 meters and less distinct at depths of 47 meters or more. With the advance of colder weather, the thermocline receded to greater depths and disappeared completely between November 16 and 20.

Winter, 1961

It is difficult to define the true winter period, as a thermocline usually exists into late fall. The winter period, as classified in this report, is the period from fall isothermal conditions to the formation of a thermocline in early spring. Surface temperatures are usually near 7.0°C or lower in the fall and 6.0° to 7.0°C in the spring. The onset of true winter isothermal conditions is preceded by unusual thermal characteristics.

Records taken in November 1961 (Cruise 50) illustrate these conditions. Stations 48, 55, and 56 clearly indicate colder heavier water overlying warmer lighter water. This may be accounted for by hysteresis in the instrument, but both the up and down traces were identical. It is more probable that, as the water cools toward the temperature of maximum density during calm periods, the mixing process is slowed because the differences in density are very small. During storm periods, with a great amount of turbulence in the water, the mixing process is accelerated.


ESCANABA
GREEN BAY
GREEN BAY
MANITOWOC
TRAVERSE CITY
LAKE MICHIGAN
MUSKEGON
MILWAUKEE
BENTON HARBOR
CHICAGO
N
SCALE
0
40 Kilometers
1
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
62
27
28
29
30
31
37
38
39
40
41
46
47
48
54
61

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN

TEMPERATURE RECORDER LOCATIONS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

The mean temperature in the southern Basin decreased by a little over 2°C between November 29 and December 21 and had fallen another 1.5°C by January 25.

By February 20 (Cruise 52) the low mid-winter temperatures had been reached which, in the deeper parts of the southern Basin down to 150 meters, were characterized by uniformity, from 2.0° to 2.3°C, from top to bottom indicating complete mixing. There is no doubt that mixing from top to bottom occurs throughout the entire winter period during every storm. The inshore area had an ice cover extending out in some locations to nearly 1.6 km. Pack ice extended over 16 km (10 miles) from shore.

A thermal bar or barrier was found on January 25 and February 20. The inshore water, out to nearly 16 km (depth 42 meters) was at or slightly less than 0.01°C. The adjacent water was nearly 2 degrees warmer and under the cold upper layers. The barrier was very sharply defined and from all appearances looked like a winter thermocline, but was actually part of a thermal bar. The bar existed, in this case, when all temperatures were several degrees less than the temperature of maximum density. A bar when temperatures are less than 4.0°C is typical during the entire winter period.

The southern basin was nearly isothermal for the entire winter. The northern basin had a true winter thermocline for the months of March and April 1962. Cruise 51 shows the changes observed in the deep hole of the Lake. Observations on March 22, 1962 between 1315 and 1920 hours indicate that a large internal wave may have occurred. Again on April 14 and April 26 changes in the thermocline occurred. On April 14 there was an 18-meter change but on April 26 the change was 40 meters. The wave period of the winter thermocline was not precisely determined, but it is probably close to those found in midsummer.

Although a thermocline is indicative of stratification, mixing to the bottom in the deep hole probably occurred during the period between the summer and winter thermocline. With a thermocline at the 180-meter depth and temperatures below maximum density in the upper 180 meters, the evidence for mixing to this depth is evident. The data indicate that the depth of mixing is a direct function of the density. When isothermal temperatures (relatively speaking) occur between 3.5° and 4.5°C, mixing might occur in Lake Michigan from top to bottom during every storm. It is also possible, if a winter thermocline does not exist, that the temperature range for mixing may be 1 or 2 degrees greater.

Spring, 1962

Cruise 1 covered two-thirds of Lake Michigan in late April and early May 1962. Nearshore temperatures were as much as 7.0°C higher than mid-lake. In general, the deep water stations of both basins were nearly the same, ranging from 1.7° to about 3.5°C. Some inshore regions already had definite thermoclines established and surface temperatures were up to 9.0°C. Cruise 2 in early June covered the eastern and far northern third of the Lake and Green Bay. The practice of taking a temperature reading before and after station sampling was begun on this cruise. Normally, the two readings are about 1 hour apart. The ship had some drift, but for all practical purposes it was in the same water mass for both soundings. In most areas a thermocline existed except for the deepest portions of the Lake. Surface temperatures ranged from 5.4° to 10.6°C on June 5 and 6 and from 6.5° to 18.5°C on June 15 and 16.

The practice of taking two bathythermograph casts disclosed what may be called short period internal waves. In a 1½-hour period the temperature changed 1.6°C at station 2, depth 6 meters. Less dramatic but similar changes occurred at other stations.

The thermocline begins its initial formation in the shallow water and works its way outward toward the center of the Lake as warming begins. During this process there is a "dome" of cold water in the central portions of the Lake, and this has been cited as evidence for clockwise circulation (18). Actually, such a "dome" will occur every spring regardless of the direction of flow. The so-called "dome" is merely a result of the physical method by which a lake warms. Since this process is reversed in fall, the Lake is in a steady transition from the shallow to deep water throughout the year. Clearly, for continental lakes such as Michigan, gross thermal changes are poor indicators of water movement except for the brief period during the month of peak solar heating.

Summer and Fall, 1962

Cruises 2, 4, 5, 6, 7, and 8 covered only the southern half of the Lake. Cruise 3 reached a small part of the northern basin. Cruises 4 and 5 were limited to 20 miles from shore, but were very intensively covered. The thermocline was well established in July. The mid-lake temperatures in the southern basin were several degrees warmer than comparable temperatures in the northern basin. The top of the thermocline varied considerably from one station to another. These variations probably resulted from BT casts during the progress of an internal wave. The maximum temperatures were reached in mid-August and early September after which the Lake began to cool slowly. A thermocline was still found in mid-November, C6-138 and 157 at 55 meters and on December 2 and 3, C8-16, 18, and 19. No records were taken by the BT in the winter of 1962-63. Data were collected by use of thermographs.

Spring, 1963

Cruises 10, 11, and 12 were made in May and June. By this time the thermocline was already established and surface temperatures were around 12.0°C and, in the very shallow areas, up to 23.0°C. Temperatures in the northern basin in May were nearly 20 degrees colder than some areas in the south. The remnant of a winter thermocline was still evident, during Cruise 11 at the 214-meter depth. During a cool spring it is very likely that a winter thermocline can remain until June. The great diversity of temperatures occurring during this period illustrates the slowness of mixing and movement that occurs in a large lake.

Summer, 1963

Cruises 13 to 18 cover the summer of 1963. Temperatures in the northern basin were lower than those observed in the southern basin in the previous year. Shore temperatures range up to 25.0°C (C15-123) and as high as 21.6°C (C16-8) for the deeper waters. Maximum temperatures again occurred in late August and early September. This type of heating and then cooling appears to be the normal trend for the Lake.

Discussion

Bathythermograph records from 1961 through 1963 have revealed several previously unknown features about the thermal distribution and the mixing rates in Lake Michigan.

Normally, southern Lake Michigan has two well defined temperature regimes: the period of summer stratification which begins in late May and lasts through November and occasionally into December, and the nearly isothermal period of constant mixing. The southern basin does not stratify in winter. Temperatures as low as 2.3°C from top to bottom indicate complete cooling and probably mixing throughout the winter-spring period. Summer stratification begins at the edges of the Lake as early as March and progresses outward and the basin becomes completely stratified by late May.

The northern basin of the Lake undergoes three temperature regimes. The summer regime does not become completely established until late June and sometimes early July. Likewise, the thermocline can be found as late as December. The winter isothermal (mixing) period is very brief for the deeper parts of the basin, lasting only one or two weeks in the early winter and again in late spring. The remainder of the winter period, the basin has a winter-type or reverse thermocline. This thermocline is deep, forming at the 120- to 180-meter depth. Although mixing can occur from top to bottom for brief periods in late winter and early fall the bottom part of the basin becomes sealed against active mixing for 11 months of the year. The total depth of the Lake and the depth of the thermocline in succeeding years indicate that a winter-type thermocline would normally occur every year.

The thermal barrier or bar appears to be a normal feature of the Lake. Recent work by Rodgers (68) in Lake Huron disclosed the effectiveness of this bar in preventing a free interchange between the shore and offshore waters during the winter period. Observations indicated that the bar forms when one zone is warmer than the temperature of maximum density and the other zone is colder. Records from Lake Michigan revealed two water masses, lying side by side with nearly a 2°C temperature difference and both below the temperature of maximum density. Even in midsummer the shore waters maintain a higher temperature differential of 5°C or more than the offshore waters. The summer separation of the two zones, in terms of distance, is not as marked as the winter period. Chemical studies do indicate, however, that there is a difference between nearshore and offshore waters in the summer, similar to those Rodgers found in Lake Huron.

The bars described by Rodgers (68) appear to be maintained by a convergence mechanism operating at the junction between the inshore water mass, usually at temperatures above, and the offshore waters at temperatures below, that of maximum density. It is suggested, however, that other factors -- for instance, topography and the effective depth of mixing -- are principally responsible for maintaining a barrier to offshore mixing.

By itself, topography exerts a powerful influence on the orientation of water movements. Because water tends to follow the contours of the Lake bottom, thus paralleling the shore, there is little interchange with the main body of the Lake, which can move in any direction. A pollutant discharged near the shore thus tends to remain inshore by the very nature of the bottom topography and shoreline orientation. For similar reasons changes in temperature can result in a thermal bar and tend to keep the two water masses separated. The shore zone due to its shallowness and smaller volume, heats more rapidly in summer and cools more quickly in winter. On this basis, a type of thermal bar appears to exist most of the year. The relative resistance to mixing appears to be related to the temperature differential and to the amount of turbulence in the system. An onshore wind generating large waves may produce mixing by forcing some of the shore water into the deeper layers of the Lake along the bottom. An offshore wind produces the opposite effect, tending to move the inshore surface waters out into the main body of the Lake. The point at which the bottom topography does not exert a controlling force on the water movement is not precisely defined. In general, in summer it is between the 7- and 10-meter contour in Lake Michigan, which corresponds to the zone where waves begin to "feel" the bottom. The depth may be somewhat greater in winter when density differences between the upper and lower layers are at a minimum. Wind mixing also is a major factor in the width of the zone. This is probably more evident in early winter than in summer because of the lack of resistance to mixing, and a well developed thermal bar may not be found.

Results - Temperature Recorder Data

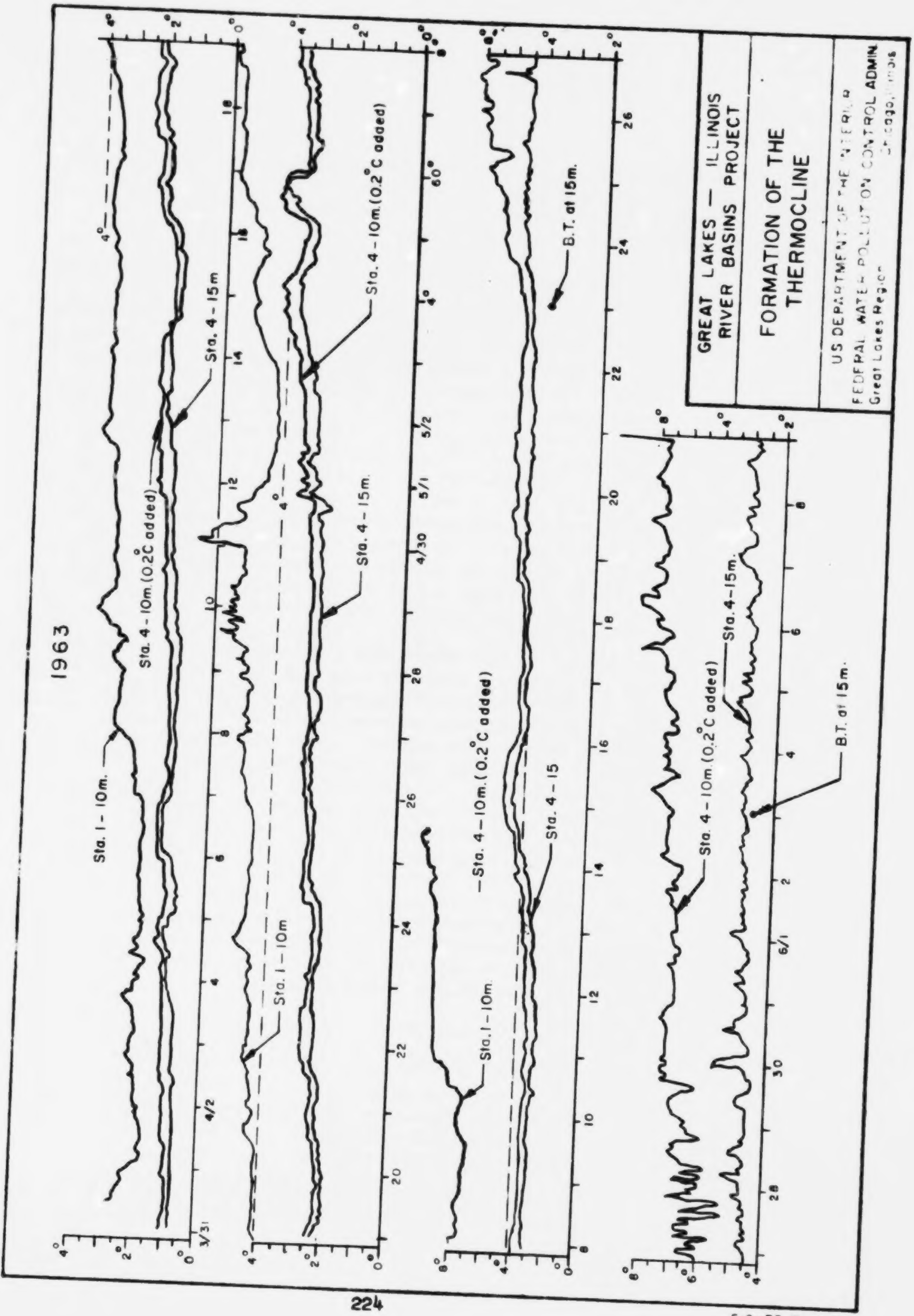
Thermographs obtained in the winter of 1962 through the summer of 1964 permit a much more complete interpretation of the thermal regime than was previously possible. Figure 7-29 shows the analog record of temperature at station 4 for the depths 10 and 15 meters. From March 31, 1963 until May 24, 1963 the temperature spread between the two levels was not discernible even though the column was gradually warming. Both cooling and warming affected the two levels at the same time. To distinguish between the two traces prior to the formation of the thermocline, a constant of 0.2°C was added to the 10-meter trace until a definite temperature separation was established. Station 1 at 10 meters was added to show the period of the thermal bar between the two stations. From April 19 to May 14, or nearly one month, the two stations were on opposite sides of the temperature of maximum density, although this is probably not necessary to maintain the barrier.

The actual formation of the thermocline began on May 23 and 24 when the mean daily temperature began to rise and the wind shifted to the east and southeast. The thermocline appears to begin its formation after the temperature of one layer is near 5.0°C, the temperature at which the density begins to decrease rapidly with increasing temperature. Once two layers separate and the upper layer warms, thereby increasing the density difference, the thermocline becomes firmly established. The temperature spread increased between the two levels and except for rare occurrences the temperatures remained apart until late fall. Temperatures taken in deep water on the BT surveys compared favorably with the thermograph for station 4 at the 15-meter depth. The thermocline begins to decay in late September after the period of maximum heating. The decay is observed as a so-called deepening of the thermocline. As the lake waters cool and the water temperatures in the epilimnion approach those in the hypolimnion, a smaller amount of energy is required to produce complete mixing between the layers.

Internal Waves

Since the summer of 1962, the Project has found internal waves on the thermocline without exception, both summer and winter. The persistence of the internal wave in the summer was not clearly identified previously although its nature and importance were predicted (54). Figure 7-30 shows the persistence of those waves.

Records appear to indicate that the internal waves, with a period near the inertial period, are standing waves. Precise timing of the



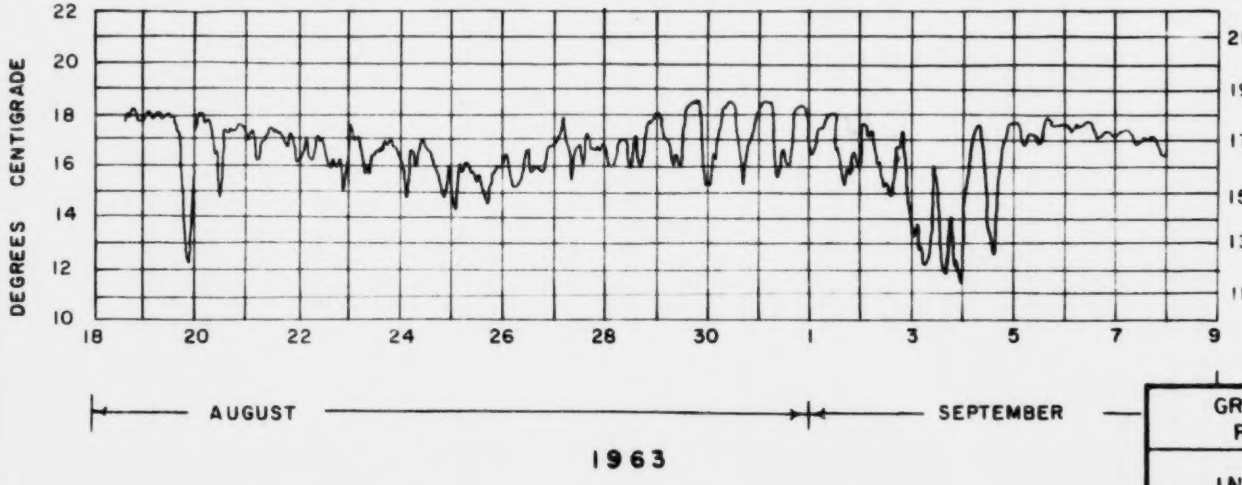
GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

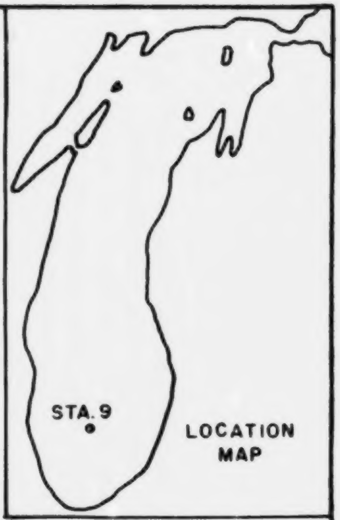
FORMATION OF THE THERMOCLINE

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-29

LAKE MICHIGAN





GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

INTERNAL WAVES AT
STATION 9 - 15 METERS

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-30

records shows that the temperature oscillations at stations 8, 9, and 10 (mid-lake) usually vary at the same time rate but not necessarily in phase (see Chapter 10). The temperatures at the edges of the Lake reflect the severe changes, with temperature oscillations up to 12°C in 3 hours. These severe changes illustrate both the upwelling and downwelling characteristics along the shore. Although large temperature changes are associated with the mid-lake oscillations, they rarely exceed 10°C in 16 hours.

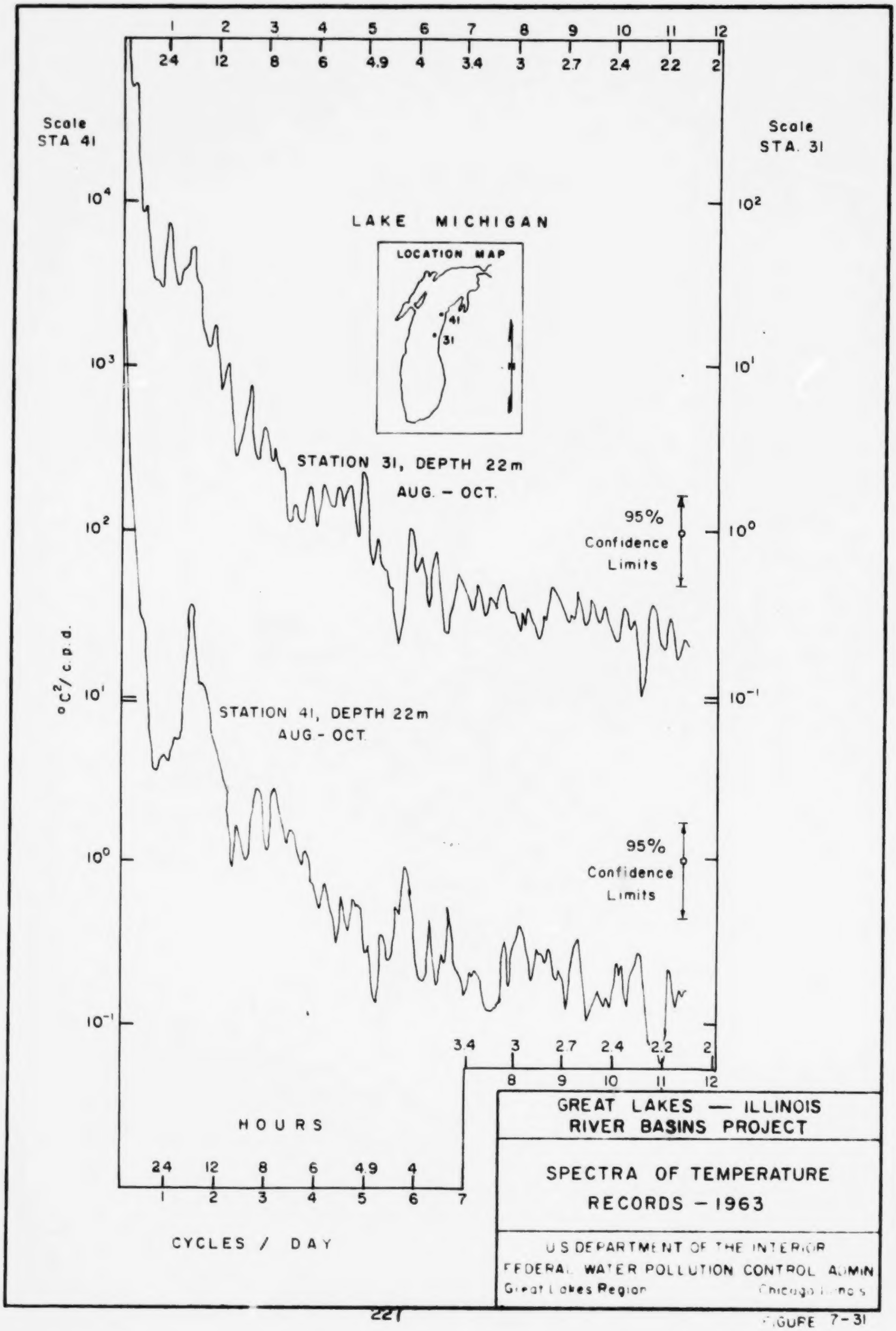
Stations 12 and 11 on opposite sides of the Lake indicate that the internal waves are occasionally also in phase.

A spectral analysis was run on seven sets of temperature data for 1963: Figures 7-31, 7-32, and 7-33. These are on a common frequency scale and are based on 750 to 2,600 hourly temperatures read to the nearest 0.1°C during the months of July through October 1963. The time span covered is as shown for each individual station. Station 11 had only 750 readings whereas the other stations had in excess of 1,600 readings.

To make the data compatible with recent spectra run on water level data in Lake Michigan by Mortimer (55), similar methods of analysis were employed. The methods of Blackman and Tukey (10) were used. A power spectrum was run on each set of data with 200 lags. The frequency scale is linear, from 0 to 12 cycles per day. The abscissa scale is amplitude squared per unit of frequency using an increment of one scale for the base of another spectrum. The use of envelopes permits an overlap of the data. Where the logarithmic scale becomes the base of a new spectrum, a double line is shown. The degrees of freedom for each spectrum vary between 16 and 22 except for station 11 which had the short record. The corresponding 95 percent confidence limits are shown on the individual figures.

Figure 7-31 shows the spectra for stations 31 and 41 on the eastern side of the Lake. At first glance, there appears to be very little similarity between the two spectra. Station 41 shows a pronounced peak in the 16- to 18-hour range whereas station 31 does not show such a sharp peak. The analog trace of the temperature record of station 31 indicates that at the station depth shown the meter was in the epilimnion for longer time periods than station 41. This may partially account for the smaller peak at this period.

The spectrum for station 31 shows a distinct peak at the diurnal, and a smaller one, of doubtful statistical significance, at the semidiurnal period. These peaks are not present in any of the other spectra presented, and this indicates that internal tides are not generated or at least are of minor importance. This is in contrast to the spectra of

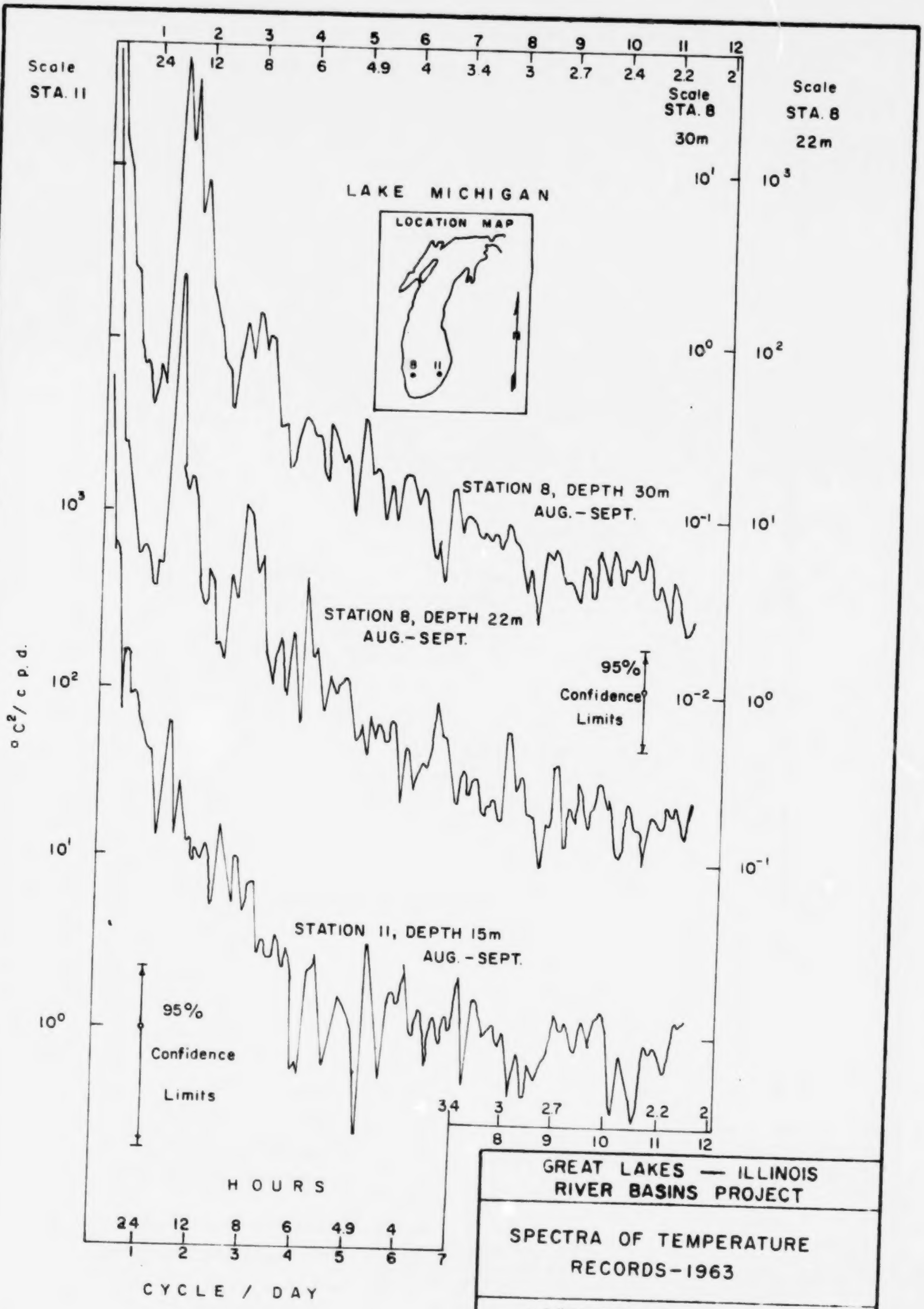


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF TEMPERATURE
RECORDS – 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 7-31

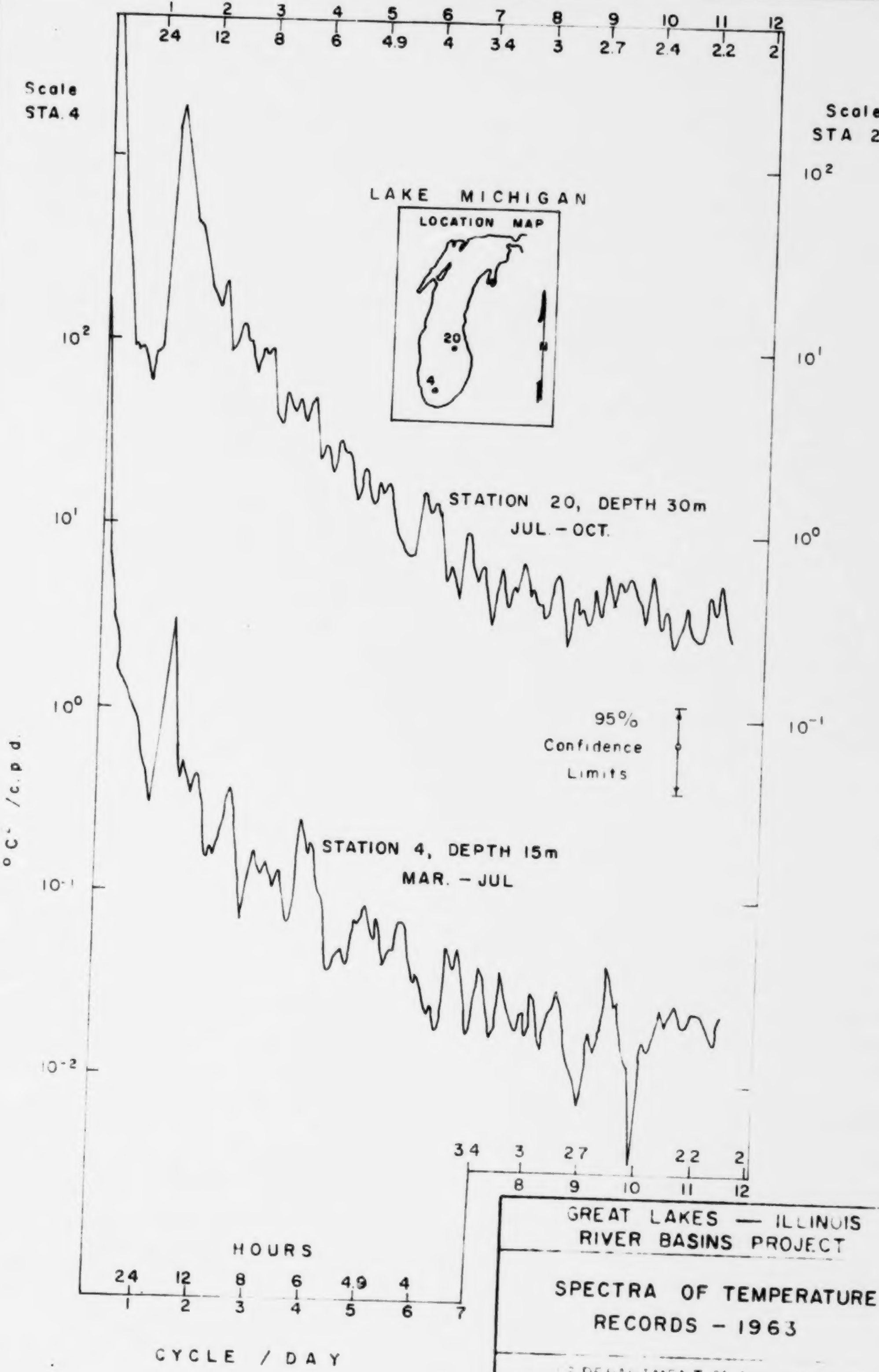


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF TEMPERATURE
RECORDS-1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 7-32



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SPECTRA OF TEMPERATURE RECORDS - 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region

7-33

surface water levels presented by Mortimer (55) in which tides, particularly the semidiurnal components, are conspicuous. A small peak at 105 hours also shows at station 11, Figure 7-32. Although the peak is small, it may be quite significant as it also appears in the current spectra and perhaps corresponds to the passage of high and low pressure systems over the Lake.

Figure 7-33 shows the spectra for stations 4 and 20 which are more mid-lake than stations 31 and 41. The 16- to 18-hour internal wave overshadows by far all other peaks.

Figure 7-32, stations 8 and 11, also shows the long period internal wave. The several peaks in the 13- to 18-hour range may be indicators of the several types of wave phenomena found on the thermocline.

The six spectra presented here may also contain peaks corresponding to the first five nodes of the longitudinal surface seiche but, if so, these are buried below the noise level of the spectrum. The long period internal wave system, near 16- to 18-hours, dominates most records. Storm inputs excite this particular frequency and maintain the internal wave. The dissipation of energy in the formation of internal waves assists in maintaining the thermocline.

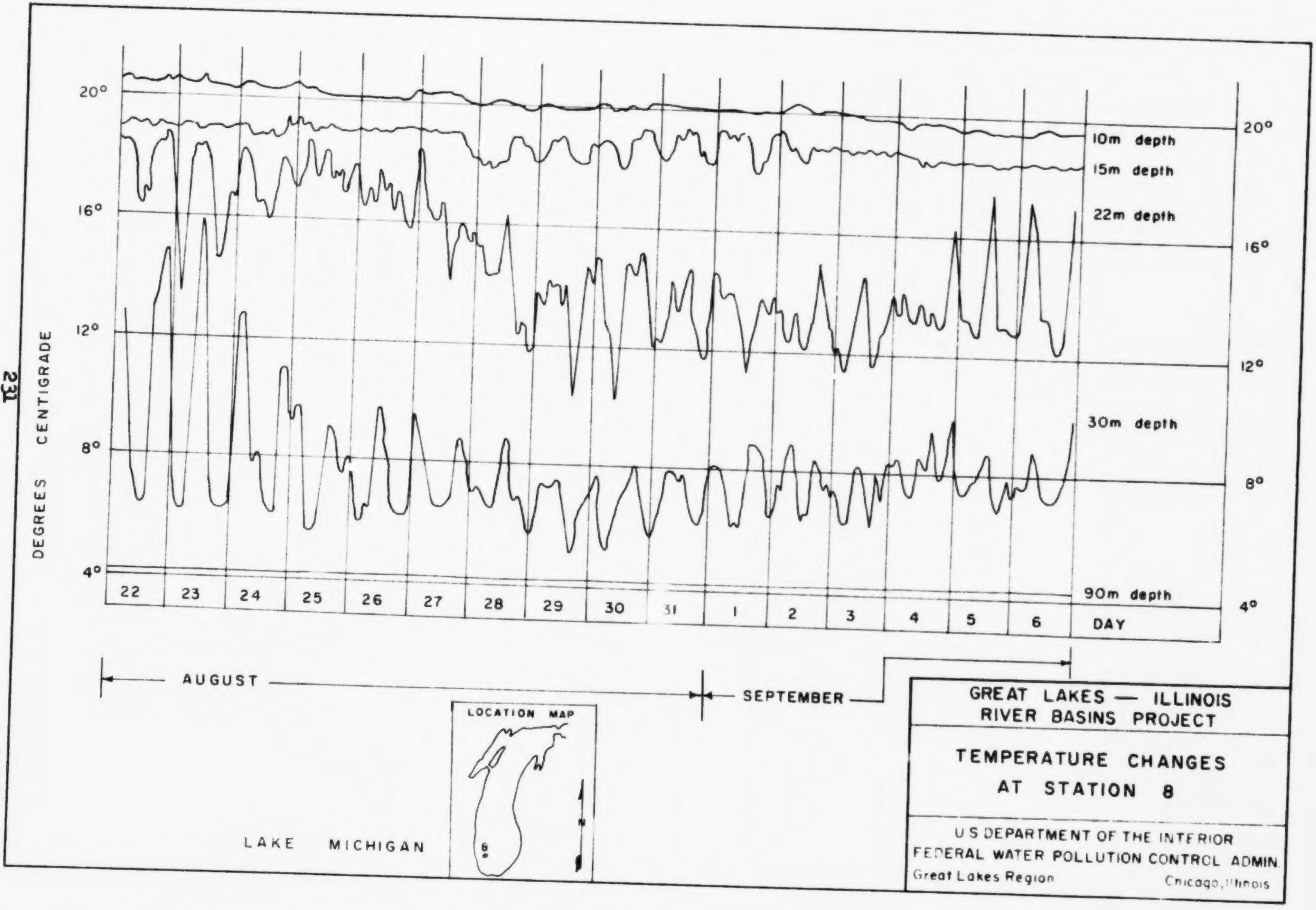
Analog Records

Figure 7-34 shows the analog record at station 8 for 10, 15, 22, and 30 meters. The records were exceptional in that they were within 0.2 percent difference in timing from one record to another for over 1,800 hours. The persistence of a regular temperature wave of close to 17 hours' period is evident and, where the phase relations can be reliably determined, appears to be in phase at all depths. As is pointed out later in Chapter 10, this indicates an internal wave of the first vertical node appropriate to a two-layered system. The interval occupied by the first 15 waves in Figure 7-34 indicates a mean period of 16.9 hours which corresponds to the highest peak in the Figure 7-32 spectrum. For the kind of period presented in Figure 7-34 it may often be more precise to determine the period visually than by spectral analysis.

Summary

Temperature records taken during the winter of 1961 through the summer of 1964 indicate that the following conditions occur:

1. Temperature profiles from bathythermographs and temperature recorders show that Lake Michigan overturns from top to bottom. The southern basin, whose maximum depth is 172 meters (565 ft.), overturns



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TEMPERATURE CHANGES
AT STATION 8

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 7-34

every year. The northern basin, whose maximum depth is 281 meters (923 feet) probably overturns every year. Overturning occurs only during early winter and early spring periods, each about one month in length. If no severe winds occur in either period, the northern basin may not mix to the bottom.

2. A winter thermocline at a depth of about 183 m (600 feet) occurs in the northern basin. Internal waves on the winter thermocline suggest that amplitude may be as great as 60 meters from trough to crest. Once the winter thermocline has been formed no mixing occurs below this depth.

3. Inshore vertical cooling and mixing occur rapidly in mid-winter with little or no horizontal exchange with the main body of the Lake. This barrier is known as the thermal bar and inhibits mixing. Even though the temperature of both areas (or zones) is less than 4°C as shown in the 1961-62 winter data, a barrier still occurs.

4. The northern basin usually lags 30 days or more behind the southern basin during the late spring and early summer warming period.

5. The southern basin cools at a more rapid rate than the northern basin.

6. Typical temperatures for Lake Michigan for a season or month of the year are difficult to define. The temperature range during one month varies considerably between the two basins at any one time. The temperature range for any given month may be expected to vary widely from year to year depending upon the severity of the weather.

7. Marked changes or configurations of the thermocline from one end of the Lake to the other are characteristic of summer conditions in the Lake.

8. Internal waves of a period near the inertial period, a little less than 18 hours, occur constantly on the thermocline and are regenerated by every storm crossing the Lake. The waves appear to be standing waves (see Chapter 10). In summer vertical velocities of 0.2 cm/sec were found by calculating the change of the isotherms from one level to another. The formation of internal waves expends energy that would normally produce mixing.

9. Alternating periods of warm surface water and cold deeper water at a water intake may be due to internal waves or tilting of the thermocline.

10. Under certain conditions, pollutants discharged into the Lake could lie on the thermocline (because of similar densities) and be

brought to the surface during the summer period, by tilting or oscillations of the thermocline.

11. The existence of thermoclines and thermal barriers during extended periods of the year greatly reduces mixing of the shallower shore waters and the waters of the hypolimnion with the main body of the Lake. Such conditions promote a buildup of persistent pollutants discharged into the isolated waters. Because of the prolonged periods during which such conditions can continue, such buildups can impair the uses of the waters adjacent to discharge points.

CHAPTER 8

DROGUE STUDIES

by

Akira Okubo and James L. Verber

Introduction

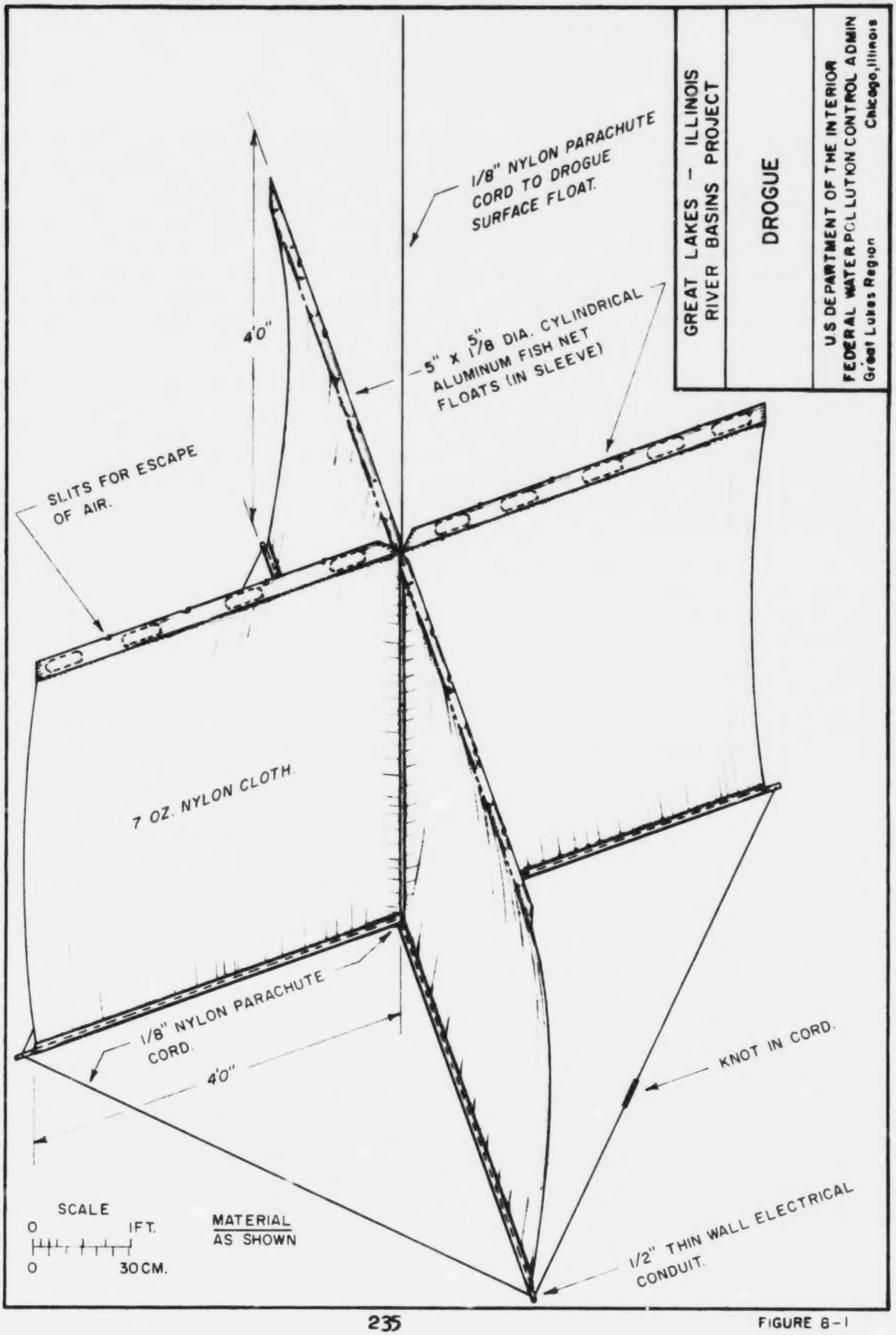
Six drogue studies were made in Lakes Michigan and Erie and at the mouth of the Detroit River. These studies were intended to obtain information on the scales and intensity of horizontal dispersion in the Great Lakes. The information, in turn, provides clues to the diffusion of pollutants discharged continuously or intermittently from sewage outfalls into the Lakes.

The basic report was prepared for the Project by Dr. Akira Okubo, Chesapeake Bay Institute, Johns Hopkins University. Dr. Okubo assisted staff members in outlining the study and contributed much toward the technology used in the study. Drogue Runs 01 and 02 were made in Lake Michigan and 03 to 06 in Lake Erie. Dr. Okubo submitted three reports, one for each Run in Lake Michigan, and a final report including Runs in Lake Erie. Also included are the field techniques used (J. S. Farlow, 31).

The approach used was to photograph from an airplane a group of small floats attached to submerged drogues (current-following devices) as they moved past an array of fixed reference markers. A series of photographs was made from a height of about 240 meters above the water surface once every 5 minutes for the first 2 hours and then once every 10 minutes for at least another hour. At this height the 22.9-cm square photographs depicted an area 360 meters square. The photos were overlapped by 80 percent so that the small floats could be located despite the large areas of glare on individual photographs. Sixteen fixed reference markers were anchored about 180 m apart in an approximately rectangular grid. They were shape- and color-coded for positive identification. The drogues were launched about 18 m apart, also in a rectangular grid pattern and were also color- and shape-coded. Between 50 and 90 drogues were used each day at each depth investigated, which gave reasonable statistical stability.

Equipment

The drogues (Figure 8-1) were made from 1.2- x 2.4-m rectangles of 198-gram (7-ounce) nylon cloth, with the upper and lower edges folded over and sewn to form tubes. Two such pieces were bent at right angles at the middle and joined together at the angles by two vertical


1/8" NYLON PARACHUTE CORD TO DROGUE SURFACE FLOAT.
4'0"
5"
-5" x 1/8 DIA. CYLINDRICAL ALUMINUM FISH NET FLOATS (IN SLEEVE)
SLITS FOR ESCAPE OF AIR.
7 OZ. NYLON CLOTH.
1/8" NYLON PARACHUTE CORD.
4'0"
KNOT IN CORD.
1/2" THIN WALL ELECTRICAL CONDUIT.
SCALE
0 1FT.
0 30CM.
MATERIAL AS SHOWN

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

DROGUE

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

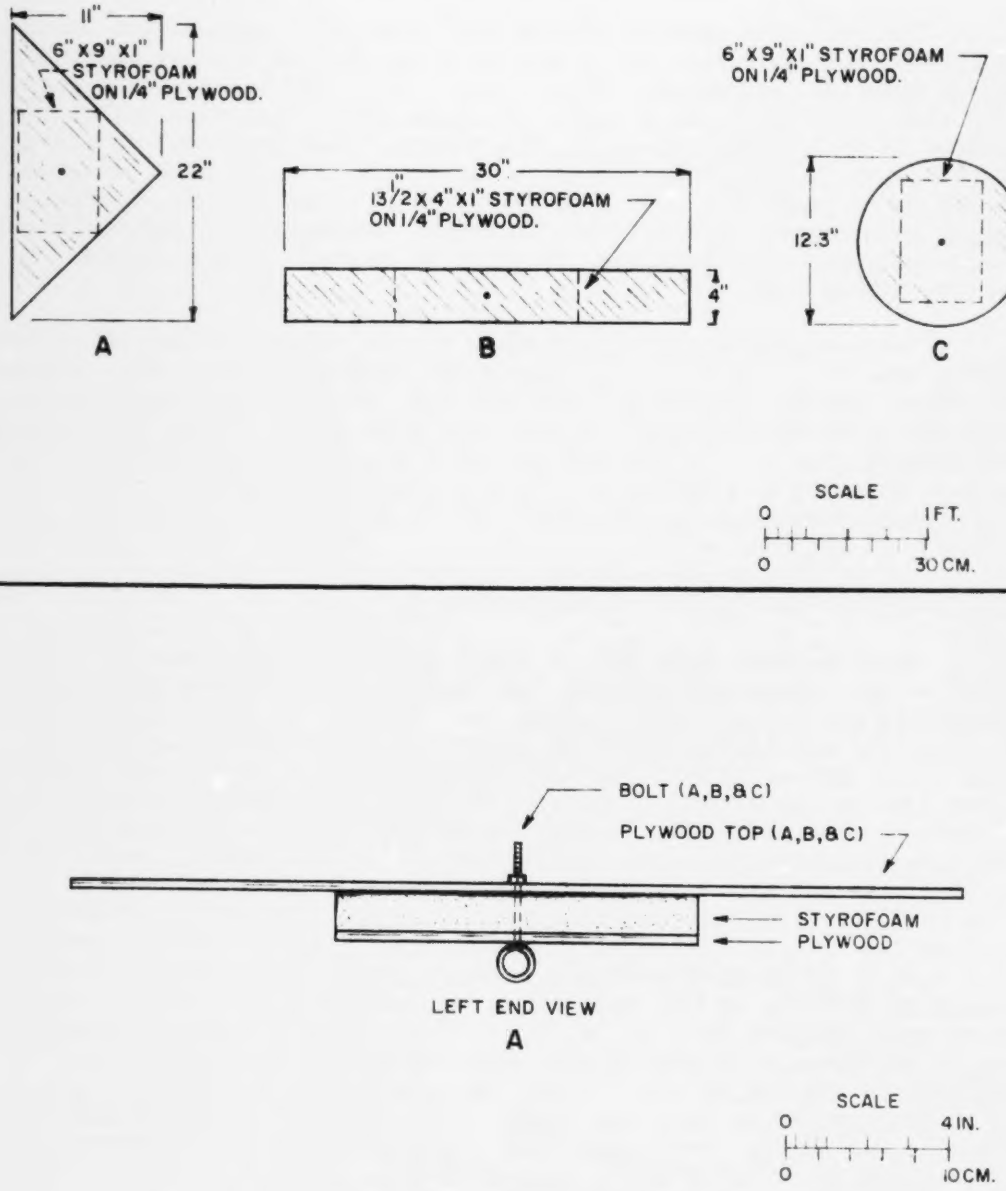
FIGURE 8-1

lines of stitching about 0.75 cm apart. Two 2.4-m lengths of 0.75-cm diameter, zinc-coated, thin-walled electrical conduit were inserted in the cloth tubes at the lower edge. Their ends were guyed by 0.19-cm diameter nylon parachute cord so that the two pieces of conduit bisected each other at right angles. The upper edges of the drogue were supported by 17 aluminum fish-net floats, each approximately 7.5 cm long and 4 cm in diameter. Slits in the upper edge of the cloth tubes containing the fish-net floats allowed air to escape freely. The assembled drogue weighed about 4.3 kg in air when dry and measured 1.2 m high by 2.4 m across overall. When submerged in lake water, each drogue weighed less than 0.22 kg (that is, one more fish-net float would make it buoyant). A length of nylon parachute cord was tied around the two pieces of electrical conduit and led up through the parallel rows of stitching holding the two panels together to a small float at the Lake surface. The weight of the submerged drogue was sufficient to keep this line as nearly vertical as a diver can judge, and so its length determined the drogue's depth. The equipment is relatively indestructible and requires no maintenance.

The surface float (Figure 8-2) was a sandwich consisting of an inch-thick piece of styrofoam held in place between two pieces of quarter-inch plywood by an eyebolt, to which the cord supporting the drogue was attached. The surface of the float had an area of 768 cm^2 and its freeboard was about 0.63 cm. Assuming a wind speed of 13 knots and a water speed of 44.7 cm/sec, the drag of the supporting elements is only about 1 percent of that of the drogue itself. The size of the drogue is such that it provides information on about 75 percent of the horizontal turbulent energy that may be expected.

Surface floats were made in triangular, rectangular, and circular shapes, and their upper surfaces were painted in one of five colors. The red, green, orange, and yellow were of reflecting paint; the white was traffic paint. As expected, the white floats were the hardest to see, because they were easily confused with white caps and glitter spots. Orange and red are the easiest colors to find from a boat or on a photograph. Rectangles are the easiest shape to pick out on the photos.

The floats were launched in order in groups of 15, each group member having the same number. Each row contained only one shape, the adjacent rows having different shapes. Each column contained only one color, the adjacent ones having different colors. This ordered alternation made it possible to keep track of the identities of 150 different floats over the period of the study. However, because the drogues tend to sink to their designed depth at different rates and because water velocity tends to change with depth, it is essential to photograph the drogues during the period of launching as well as after they are all launched.



11"
6" X 9" X 1" STYROFOAM ON 1/4" PLYWOOD.
22"
A
30"
13 1/2 X 4" X 1" STYROFOAM ON 1/4" PLYWOOD.
4"
B
6" X 9" X 1" STYROFOAM ON 1/4" PLYWOOD.
12.3"
C
SCALE
0
1 FT.
0
30 CM.
BOLT (A, B, & C)
PLYWOOD TOP (A, B, & C)
STYROFOAM
PLYWOOD
LEFT END VIEW
A
SCALE
0
4 IN.
0
10 CM.

MATERIAL
AS SHOWN

FINISH
REFLECTING PAINT

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

DROGUE SURFACE FLOATS

DROGUE STUDY

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

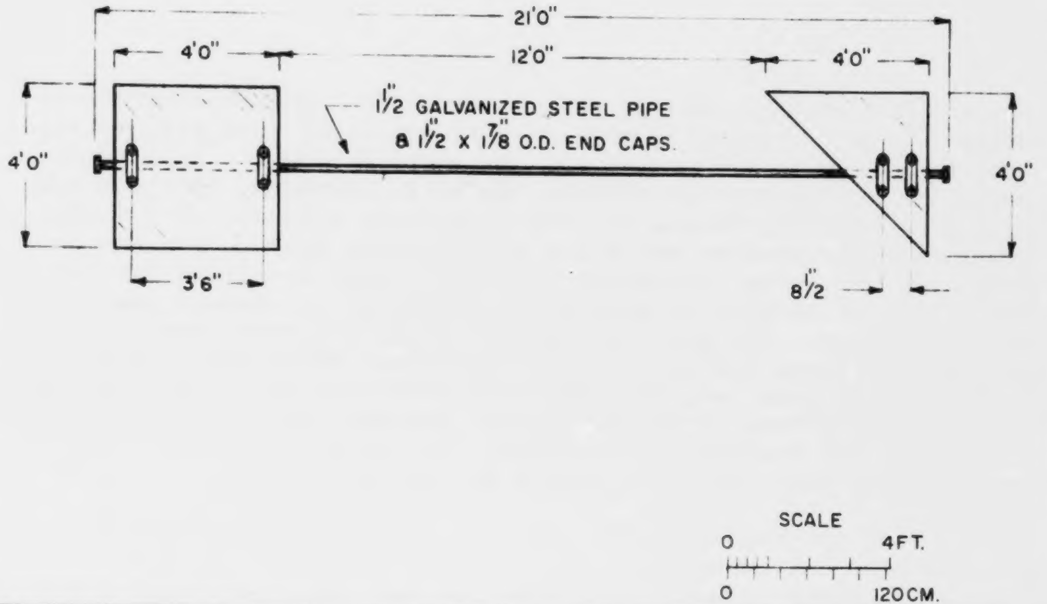
FIGURE 8-2

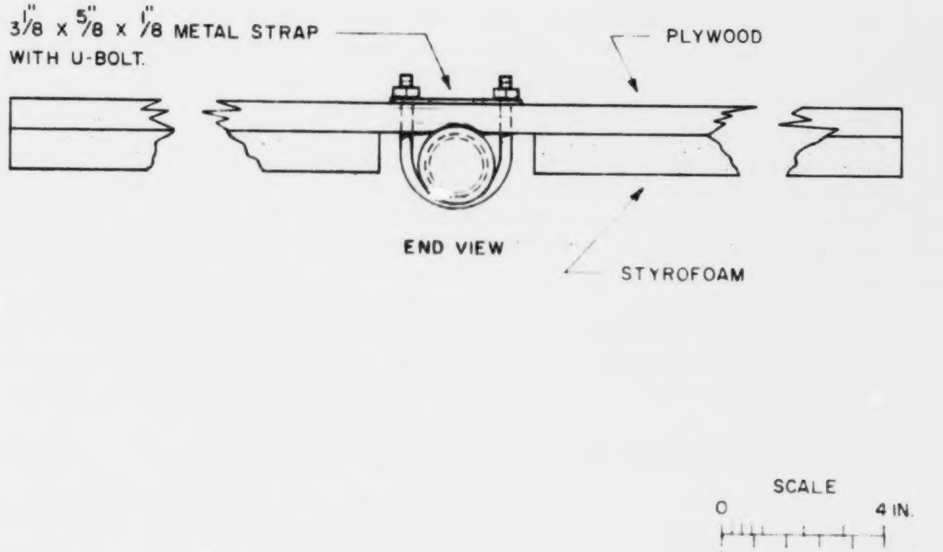
The reference markers (Figure 8-3) were each made of two sheets of plywood and styrofoam which supported the ends of a 6.3-m length of 3.8-cm diameter, galvanized steel pipe. One float was a square 1.2 m on a side, the other was a right triangle made by cutting one of the squares in half along a diagonal. The floats, which were made of 1.9-cm plywood with 25.4-cm styrofoam sheets nailed on the underside, were held to the upper side of the pipe by pairs of u-bolts. The pipes were capped to increase buoyancy. Eighteen-inch sections of old railroad rails were used as anchors and fastened to each end of the marker by 0.63-cm manila line.

The photographer took vertical photos with a Zeiss RMK 15/23 camera with a 153 mm lens. The camera was loaded with five 22 m rolls of Kodak aerial Ektachrome spliced end to end. This magazine was replaced by another similar one about the time the photographic interval was changed from 5 to 10 minutes, making a total of about 255 m of film used on each day of field work. If camera tilt is less than 2 degrees, the maximum distortion in the corner of the 22.9-cm square negative is, at most, 10 microns.

Field Methods

On an average field day, a larger vessel (14 m or more in length) carrying the assembled drogues and reference markers and two smaller vessels (about 6.0 m long) reached the study area about 0830. Test drogues were set to the depths of interest, and watched for about 1/2 hour while the reference markers were readied for launching. When a clear idea of the direction of drift was obtained, three parallel lines of reference markers were launched about 180 m apart and parallel to the direction of drift. The larger vessel cruised slowly tossing off markers with one anchor attached, while the small boats followed behind attaching the second anchors in a taut fashion so the markers would neither translate nor rotate. Three lines of four reference markers each took about 20 minutes to set. (There were four additional markers remaining on board at the end of this first operation.) After these first dozen markers had gone in, the test drogues were checked again to see if any drastic changes in direction had occurred. By that time the photo plane was making a high level run (about 1,800 m above the water) to be able to get at least one frame showing all the reference markers. While it was making this run, the larger vessel started setting the deep drogues about 18 m apart, working upwind, laying successive cross-wind lines. When the equipment was in good order, it took about 45 minutes to set some 75 drogues between two lines of reference markers. The small boat followed the larger setting vessel, untangling any equipment which became fouled during launching and righting capsized surface floats. After the deep drogues were in, the shallow drogues were


21'0"
4'0"
12'0"
4'0"
1½" GALVANIZED STEEL PIPE
8 1½" x 1⅞" O.D. END CAPS.
4'0"
4'0"
3'6"
8½"
SCALE
0
4FT.
0
120CM.


3⅛" x ⅝" x ⅛" METAL STRAP
WITH U-BOLT.
PLYWOOD
END VIEW
STYROFOAM
SCALE
0
4 IN.
0
10CM.

MATERIAL
AS SHOWN
FINISH
REFLECTING PAINT
NOTE:
STYROFOAM NAILED TO PLYWOOD

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

REFERENCE MARKER

DROGUE STUDY

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-3

launched in a parallel lane of reference markers. Drogues at different depths have been observed to move at right angles and also in directions directly opposed to one another for some hours at a time. This was one reason for putting out test drogues. The outer boundaries of the groups of drogues should be checked at least once every 3/4 hour, so that additional reference markers can be put in or others shifted in such a way as to keep the ground surrounded. General trends were noted and plans were laid in advance to maintain a usable grid of markers among the drifting drogues. The photo plane made additional high level runs as necessary. It began making low level runs (about 240 m above the water) as the first drogues were set. These runs were made every 5 minutes for approximately 3 hours, after which the interval was increased to 10 minutes for the remaining 2 to 3 hours. At the end of about 6 hours, the plane had used some 255 m of film and most of its fuel.

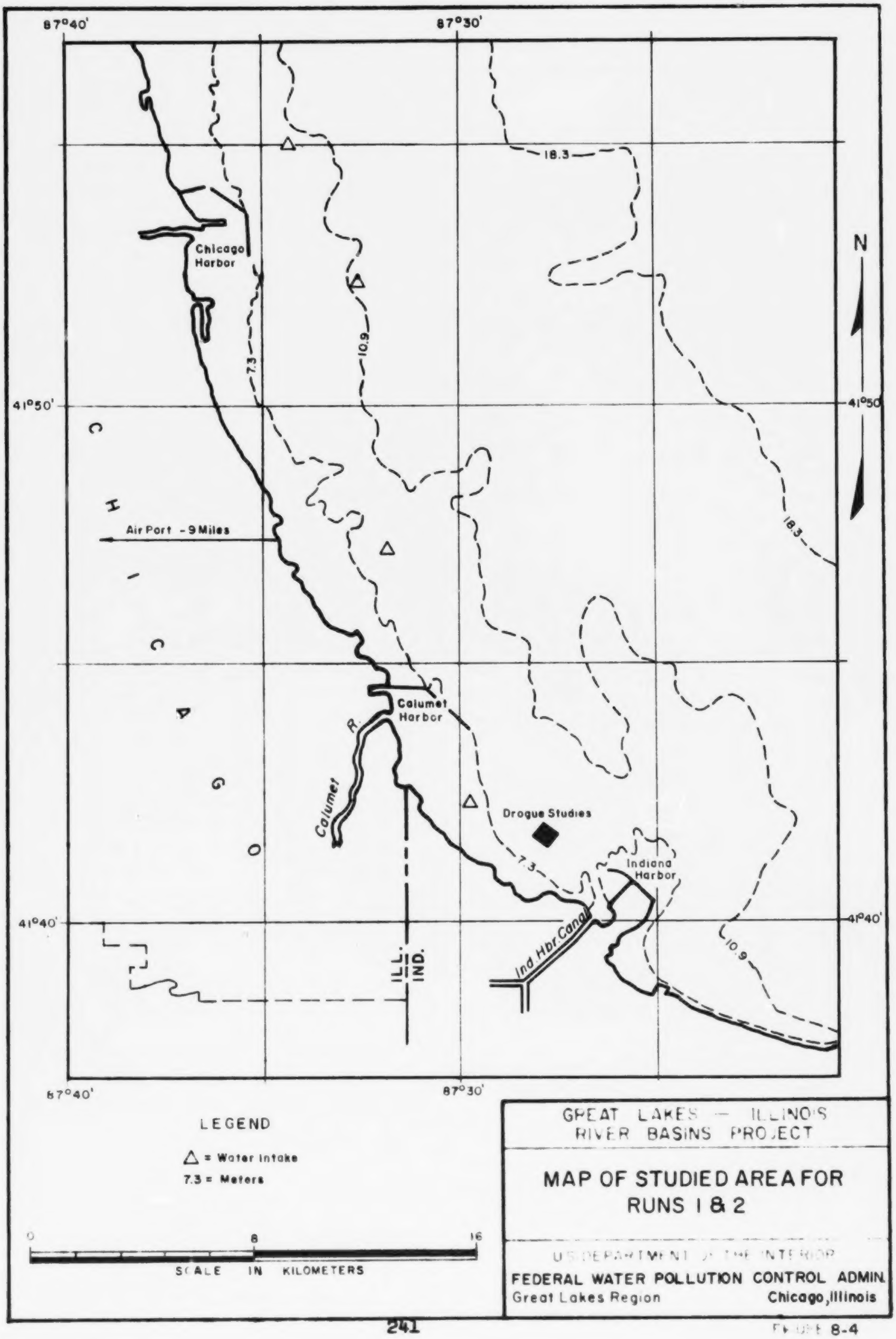
After the plane departed all boats started collecting drogues, and also reference markers, if this was the last day of the study. At least 3 hours were allowed, as finding the last half dozen usually took considerable time. About 95 percent of the drogues were recovered.

Analysis Methods

The raw data from these studies were reduced to yield a time series of the locations of a group of drogues at each depth. The positions of the drogues were transformed by a computer program into an absolute coordinate system fixed to the Lake. New York University provided computer programs for the studies. The following calculations were conducted by computer: the means, variances, and covariances of each group of drogues at appointed times, the distance-neighbor separations (the pair-program), and the dispersion of drogues with respect to their initial positions. A CalComp plotter was used in the program so that graphs of a group of drogues could be prepared for each depth at selected times. Lagrangian correlations of the drogue displacements were also computed for two typical runs; however, the results are not included in this report, since meaningful conclusions could not be derived from them.

Description of Experimental Results

On June 25 and 26, 1964, two studies (Run 1 and Run 2) were made in Lake Michigan about 2.4 km WNW of Indiana Harbor, Indiana, East Breakwater Light, where the water depth is about 8.1 m (Figure 8-4). On July 15 and 16, two studies (Run 3 and Run 4) were conducted in Lake Erie about 8 km WSW of Colchester, Ontario, where the depth of water is approximately 7.5 m (Figure 8-5). Finally, on August 15 and 16, two more studies (Run 5 and Run 6) were made in Lake Erie about 5.6 km west of Cleveland, Ohio, West Pierhead Light, where the depth of water is

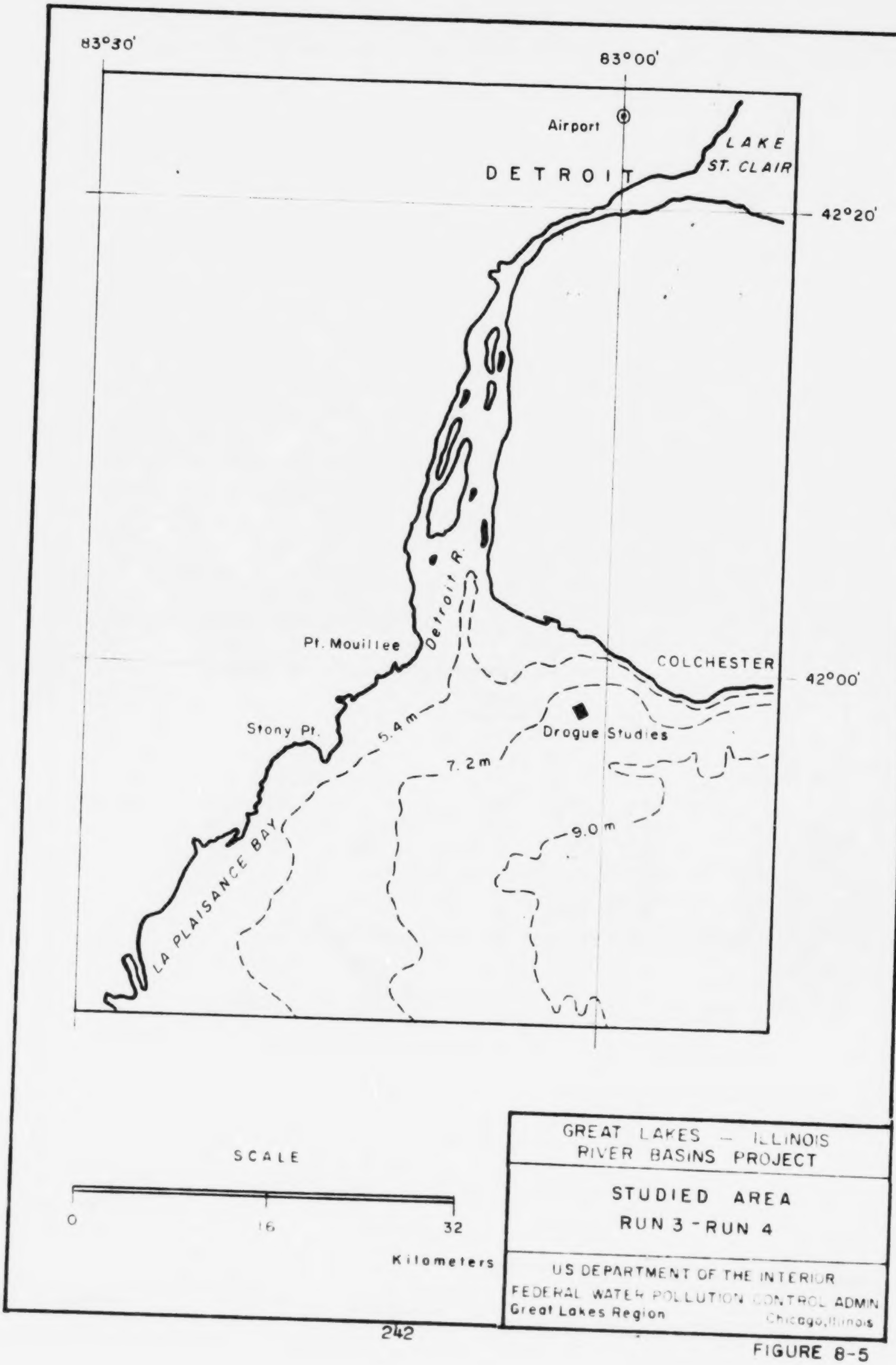

87°40'
87°30'
N
41°50'
41°40'
18.3
10.9
7.3
Chicago Harbor
Air Port - 9 Miles
CHICAGO
Calumet Harbor
Calumet R.
Drogue Studies
Indiana Harbor
Ind. Hbr. Canal
ILL.
IND.
LEGEND
△ = Water Intake
7.3 = Meters
0
8
16
SCALE IN KILOMETERS

GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

MAP OF STUDIED AREA FOR RUNS 1 & 2

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-4


83°30'
83°00'
Airport
LAKE
ST. CLAIR
DETROIT
42°20'
Detroit R.
Pt. Mouillee
COLCHESTER
42°00'
Stony Pt.
5.4 m
Drogue Studies
7.2 m
9.0 m
LA PLAISANCE BAY
SCALE
0
16
32
Kilometers

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STUDIED AREA
RUN 3 - RUN 4

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-5

about 12.6 m (Figure 8-6). All of the aerial films have been developed, but computer runs have not been processed for Run 4, so this report will exclude analysis of Run 4.

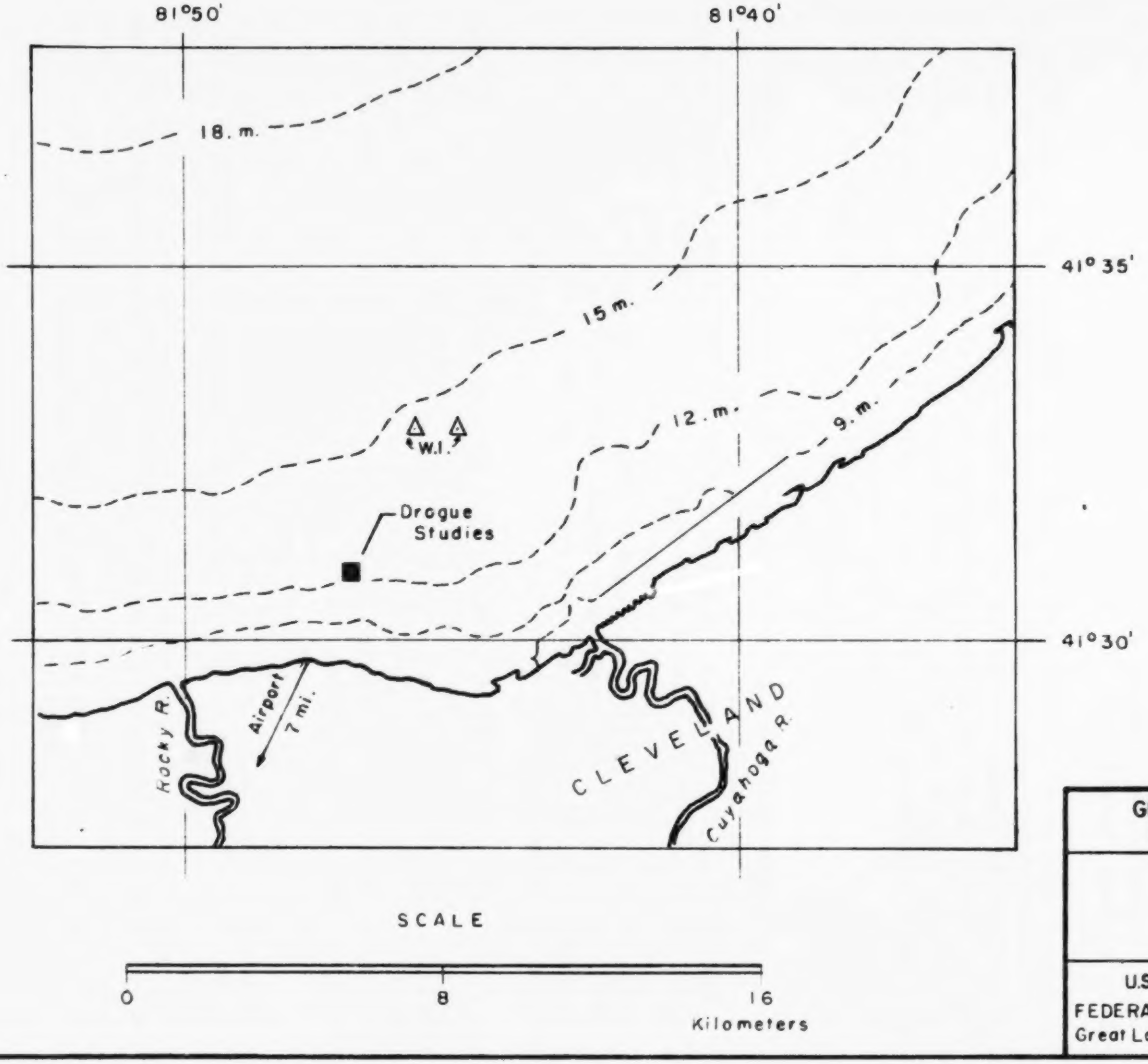
On a typical experiment or run, a total of N_1 drogues was released at 6.1 m depth, each being launched about 18.0 m apart in a rectangular grid pattern. In Runs 2, 3, and 6, after the 6.1-m drogues were released, a total of N_2 drogues was also released at 1.5-m depth in a similar manner.

A series of aerial photographs was taken from an altitude of about 240 m once every 5 minutes or so for the first 3 hours and then approximately every 10 minutes for the rest of the experimental period. The probable error in locating drogues is estimated at 1 to 2 meters, the higher figure to hold for later parts of the experimental period. The early photos for Runs 2, 3, and 6 were not used in the computer programs. Thus, for these runs, the analysis of diffusion covers the period after both groups of drogues were set in the water. General information on the runs is contained in Table 8-1.

Drogue positions at some typical times are shown in Figures 8-7 to 8-11, where the coordinate system is taken in such a way that the X-axis points to the east and the Y-axis to the north. Some drogues could not be located, chiefly because they were outside the field of the aerial photographs. On a few occasions some drogues failed to be detected even though they supposedly were in the field of the photos. The approximate positions of those missing drogues, however, were obtained by interpolating between the preceding and subsequent positions whenever possible.

Group size did not always tend to increase with time. Whereas the 1.5-m drogues in Runs 2 and 6 and the 6.1-m drogues in Runs 1, 2, and 3 exhibited the tendency of growth of group size with time, characteristic of turbulent diffusion, the anticipated increase in group size was not immediately recognizable for the 1.5-m drogues in Run 3 and the 6.1-m drogues in Runs 5 and 6.

Figures 8-12, 8-13, and 8-14 illustrate the time behavior of the standard deviation for all the runs. There was, in fact, very little dispersion of the drogues for Runs 3, 5, and 6 as was mentioned previously; the drogues were dispersed over approximately the same area at the end of a few hours as at the beginning of the experiment, and at times a certain number of drogues was noticeably reconcentrated in one location or another (see Figure 8-10). It is evident that those drogues encountered temporary convergences present at the depth of water where the drogues were located.


81°50'
81°40'
41°35'
41°30'
18. m.
15 m.
12. m.
9. m.
W.I.
Drogue Studies
Airport 7 mi.
Rocky R.
CLEVELAND
Cuyahoga R.
SCALE
0
8
16
Kilometers

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

STUDIED AREA
RUN 5 – RUN 6

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

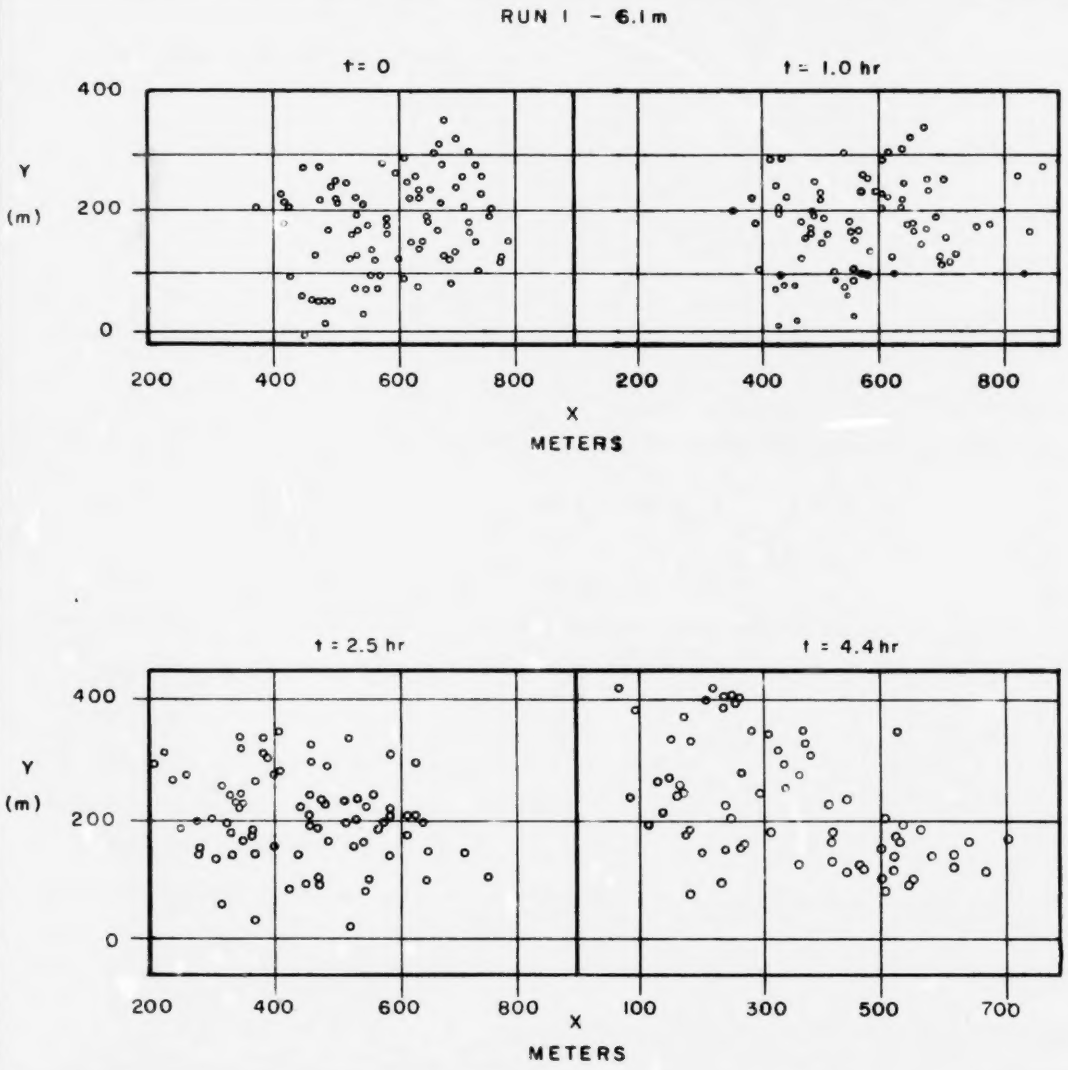
FIGURE 8-6

TABLE 8-1

GENERAL INFORMATION ON EXPERIMENTAL RUNS*

Run no.	Date	Location	Depth of water		Depth of drogues		Duration of run	Dist. from shore		Initial gr. sz.	Final gr. sz.	Vel. of drogues	Wind sp.	Wind factor	No. of drogues
			(m)	(ft)	(m)	(ft)	(EST)	(miles)	(km)	(m)	(m)	(cm/sec)	(cm/sec)	%	
1	6/25/64	L. Michigan	8.1	27	6.1	20	11.45-16.46	1 1/4	2.4	310x 470	500x 1000	3.0	400	0.8	90
2	6/26/64	L. Michigan	8.1	27	1.5	5	11.43-15.30	1 1/4	2.4	200x 200	300x 600	3.4	420	0.8	70
					6.1	20				300x 600	300x 1000	2.2	420	0.5	70
3	7/15/64	L. Erie	7.5	25	1.5	5	12.25-15.45	4 1/2	8.0	250x 400	250x 400	3.1	380	0.8	75
					6.1	20				350x 1000	400x 1200	1.5	380	0.4	75
5	8/15/64	L. Erie	12.6	42	1.5	20	11.14-16.50	1 1/2	5.6	350x 450	350x 450	2.0	320	0.6	85
6	8/16/64	L. Erie	12.6	42	6.1	5	12.27-16.20	1 1/2	5.6	160x 240	220x 340	6.0	360	1.7	50
					1.5	20				250x 500	250x 500	3.0	360	0.8	75

*See text for definitions.



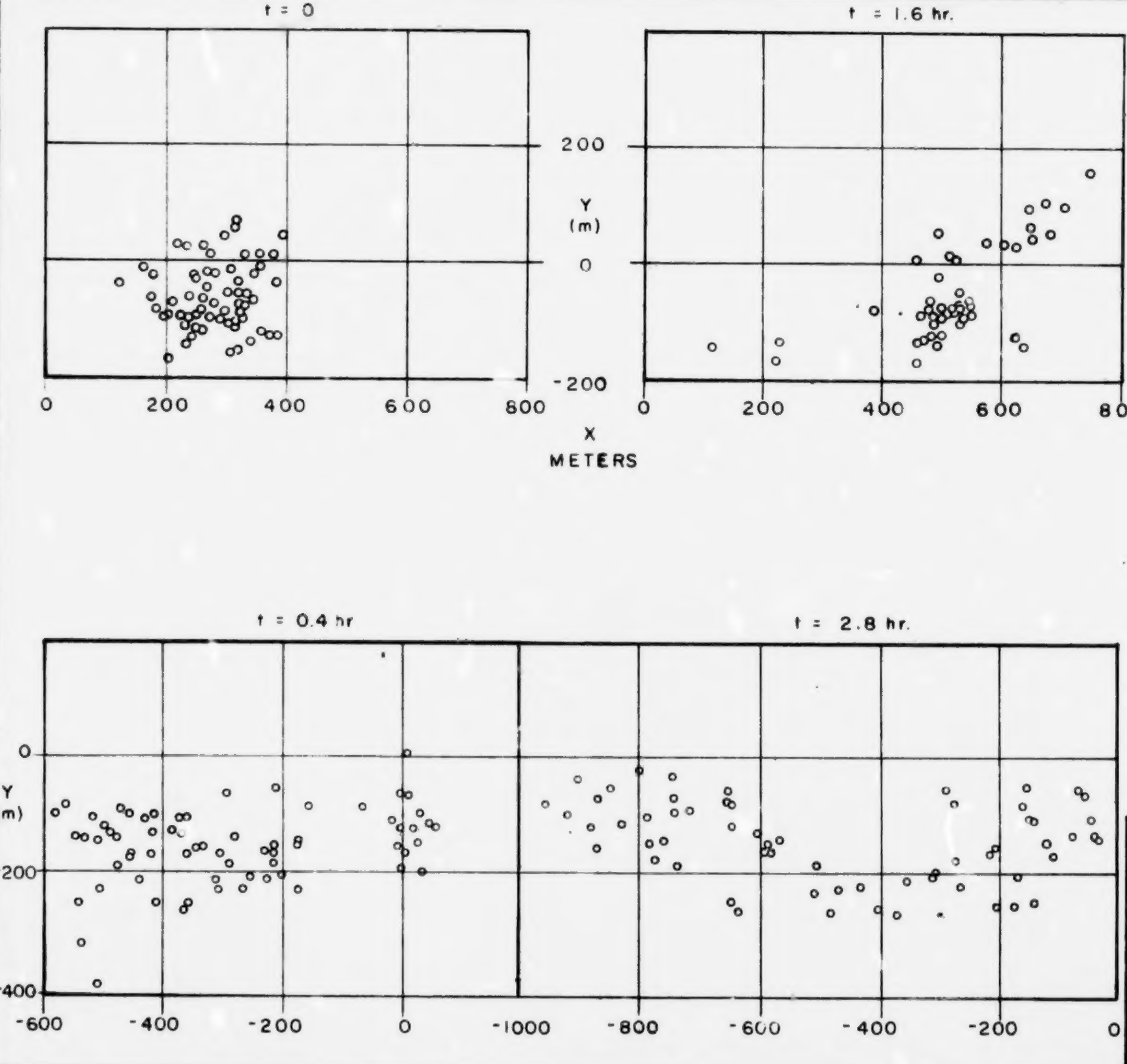
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

POSITION OF DROGUES
RUN I

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-7

RUN 2 - 1.6 m



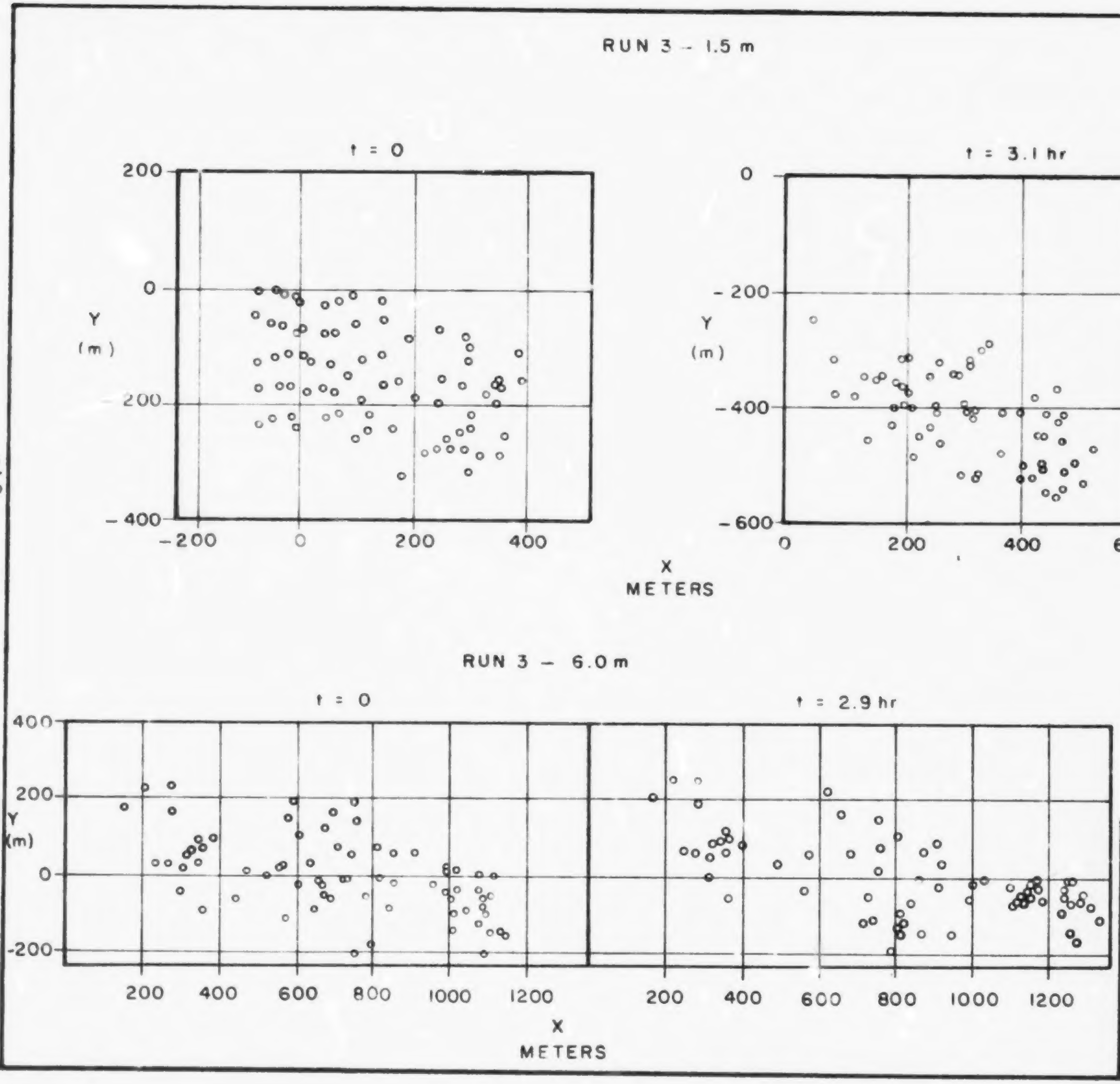
GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

POSITION OF DROGUES

RUN 2

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-8



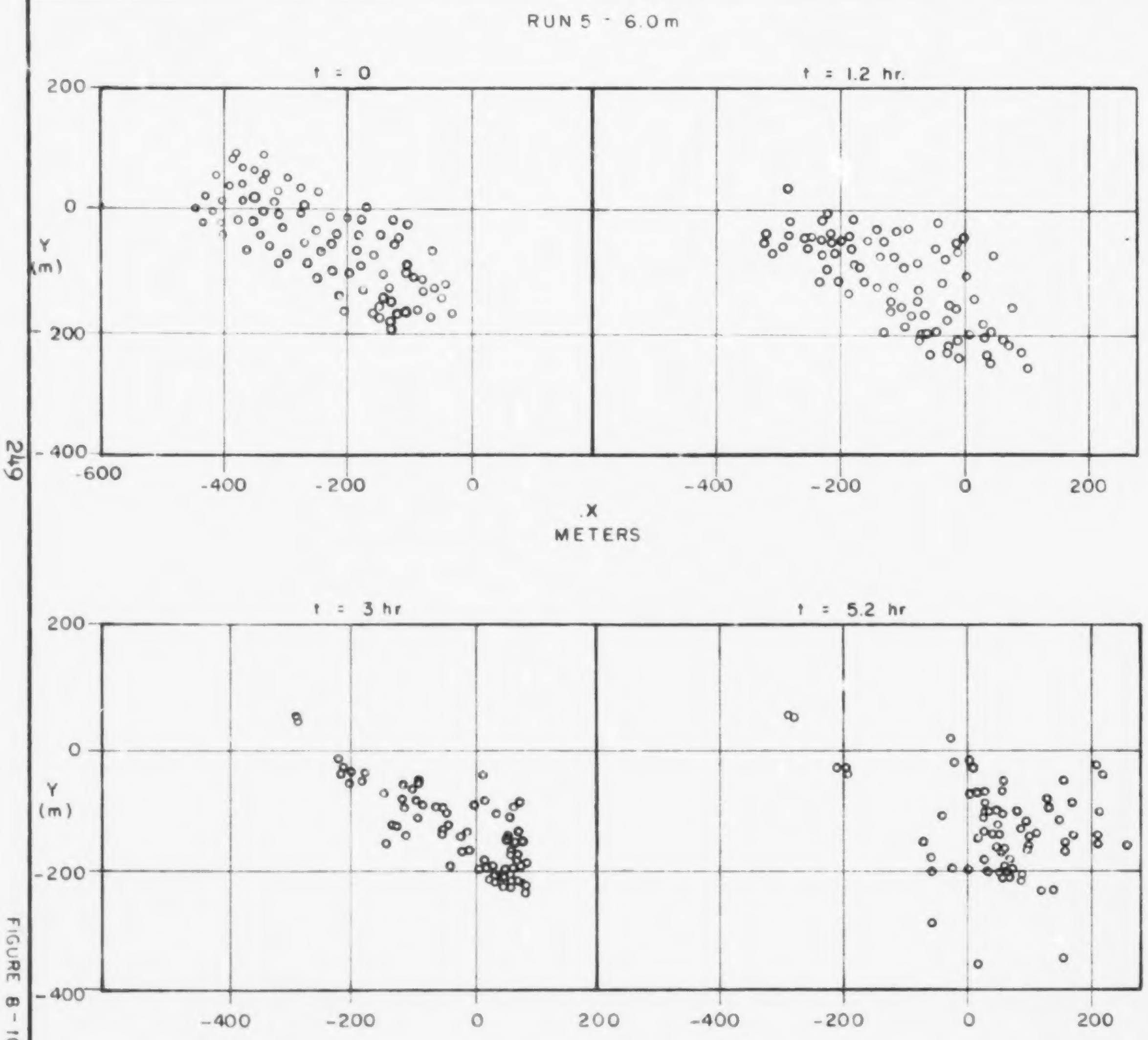
GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

POSITION OF DROGUES

RUN 3

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-9

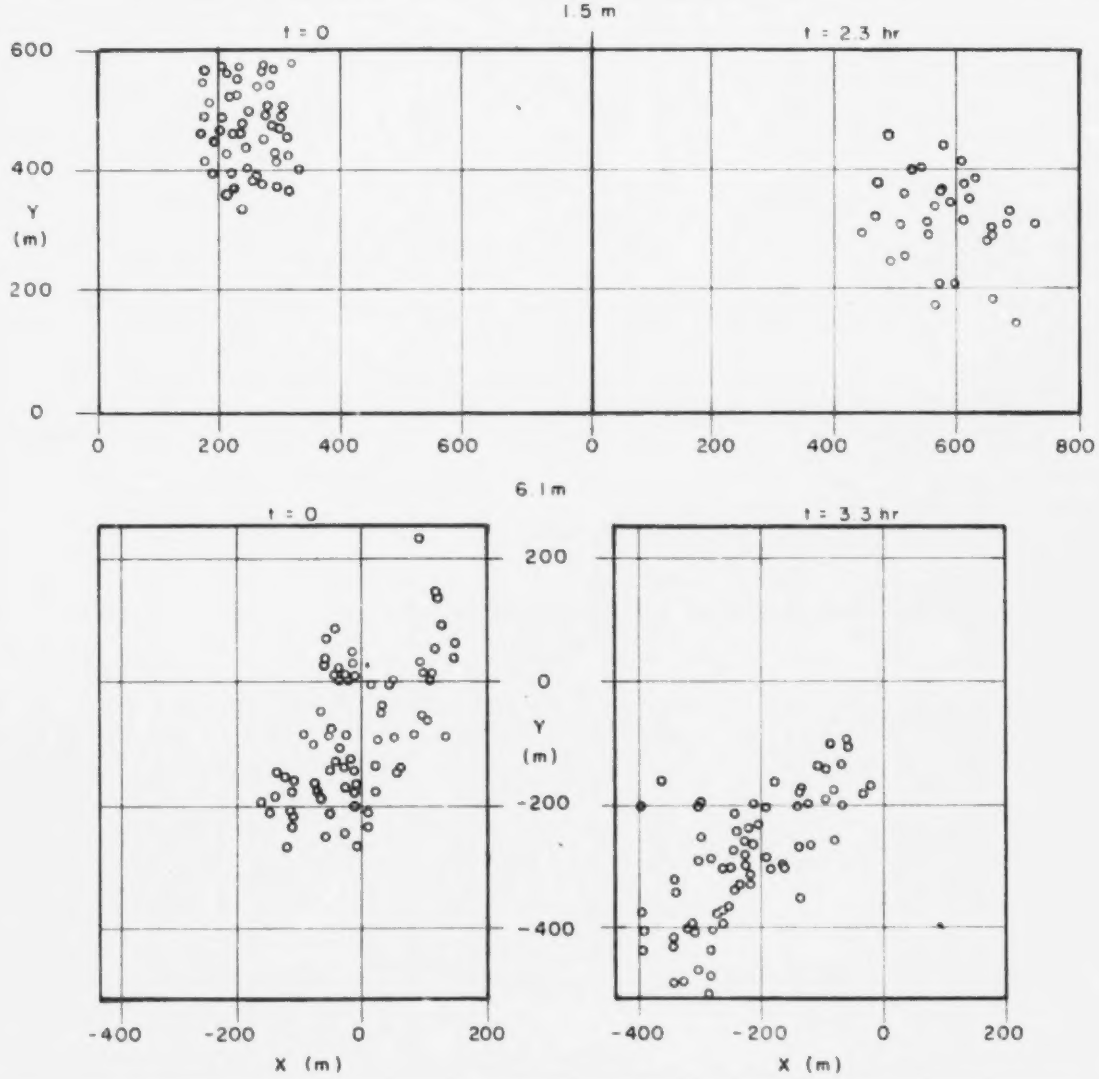


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

POSITION OF DROGUES
RUN 5

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-10



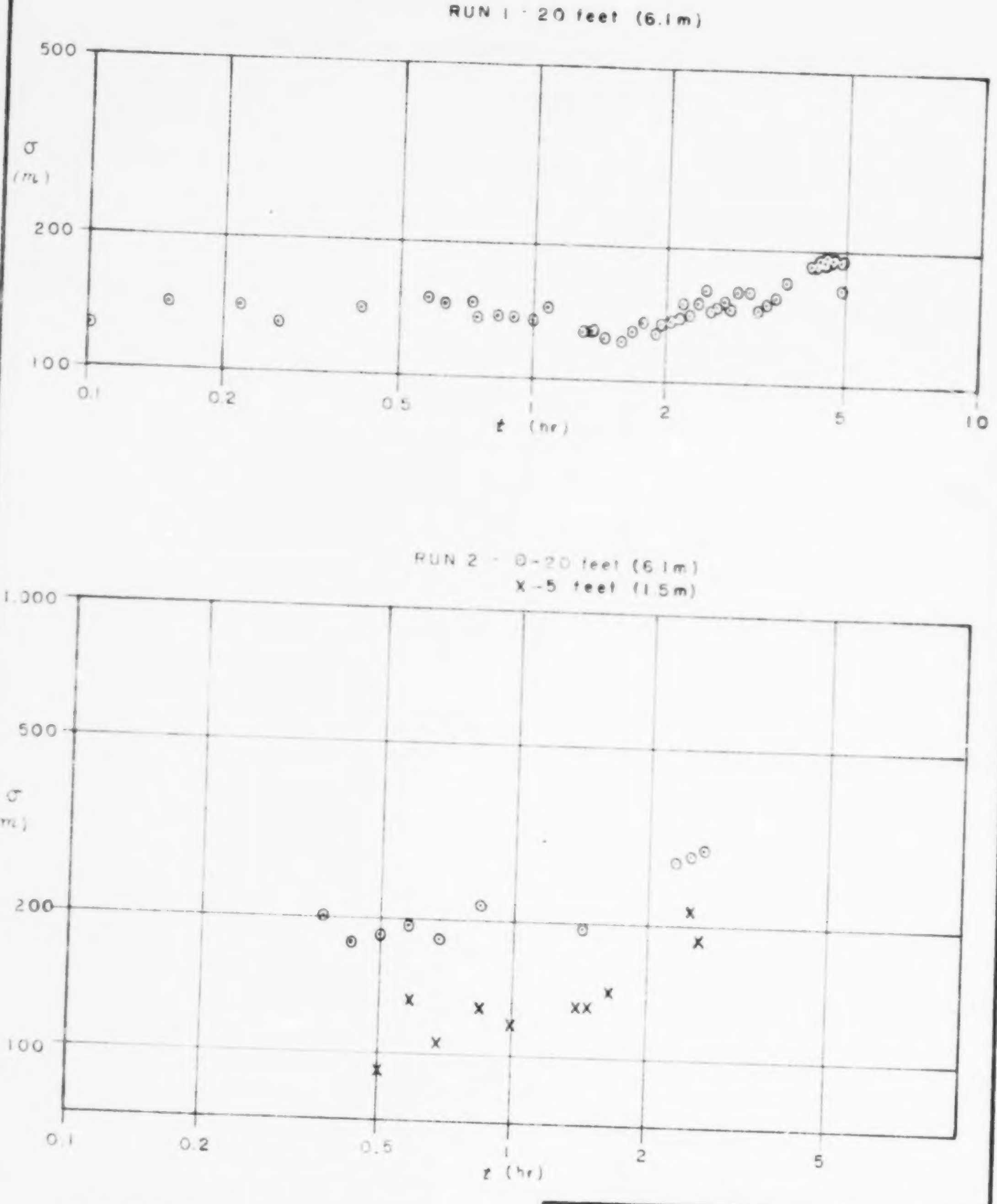
GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

POSITION OF DROGUES

RUN 6

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE B-11



TIME VARIATION OF STANDARD DEVIATION IN THE GROUPS OF DROGUES

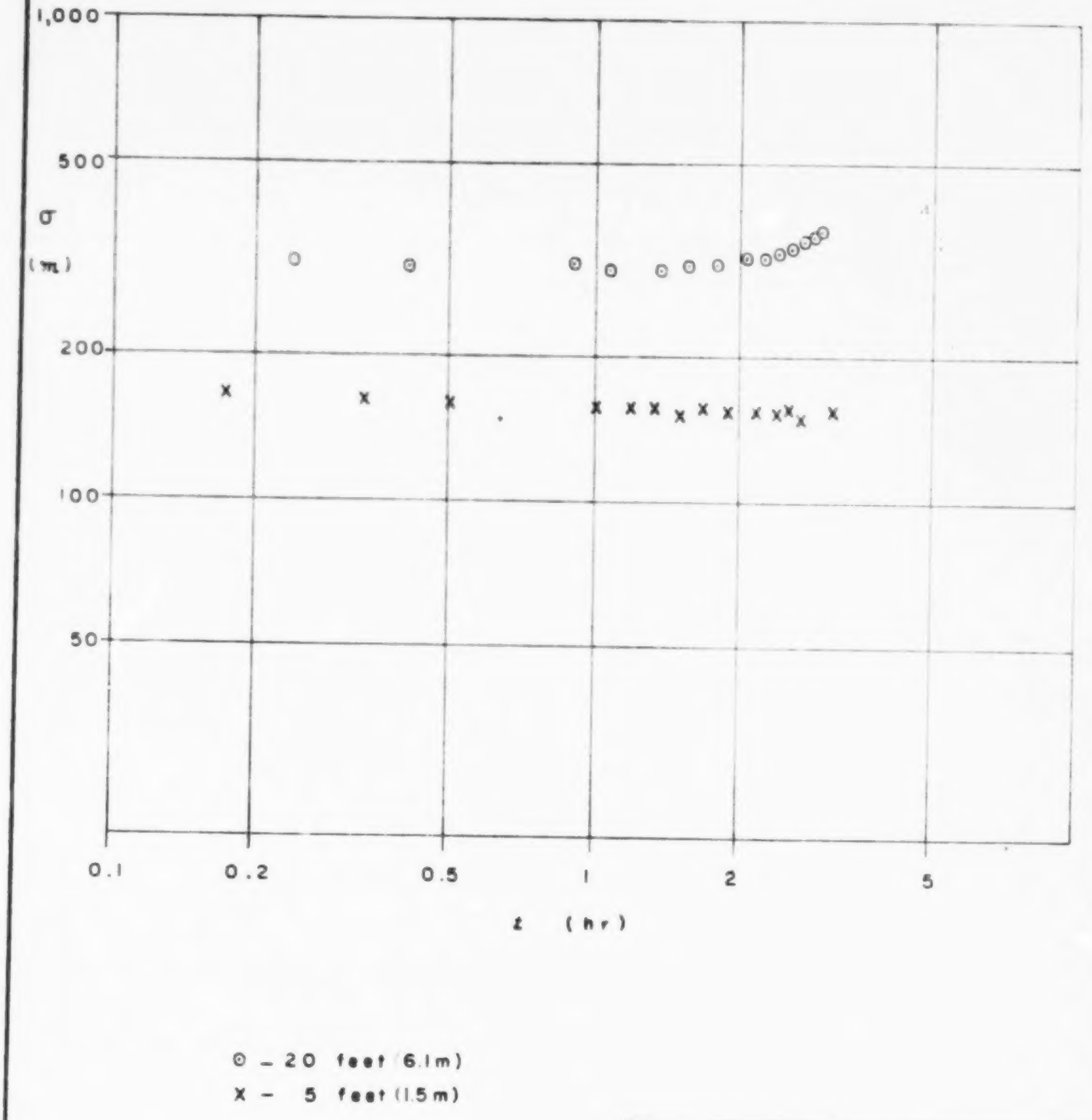
GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

TIME VARIATION
RUN 1 - RUN 2

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-12

TIME VARIATION OF STANDARD DEVIATION IN THE GROUPS OF DROGUES

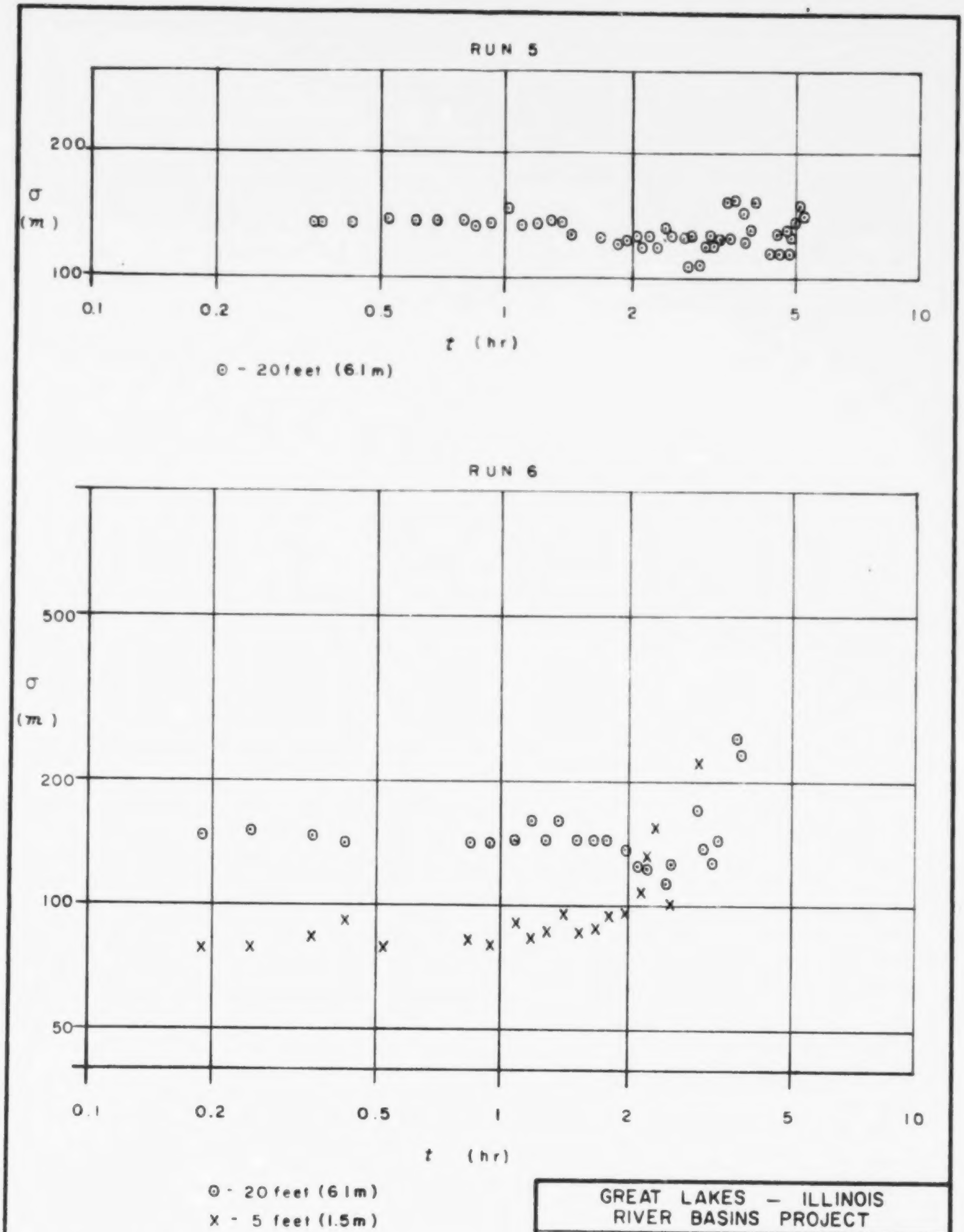


GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

TIME VARIATION
RUN 3

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-13



TIME VARIATION OF STANDARD DEVIATION IN THE GROUPS OF DROGUES

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TIME VARIATION
RUN 5 — RUN 6

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-14

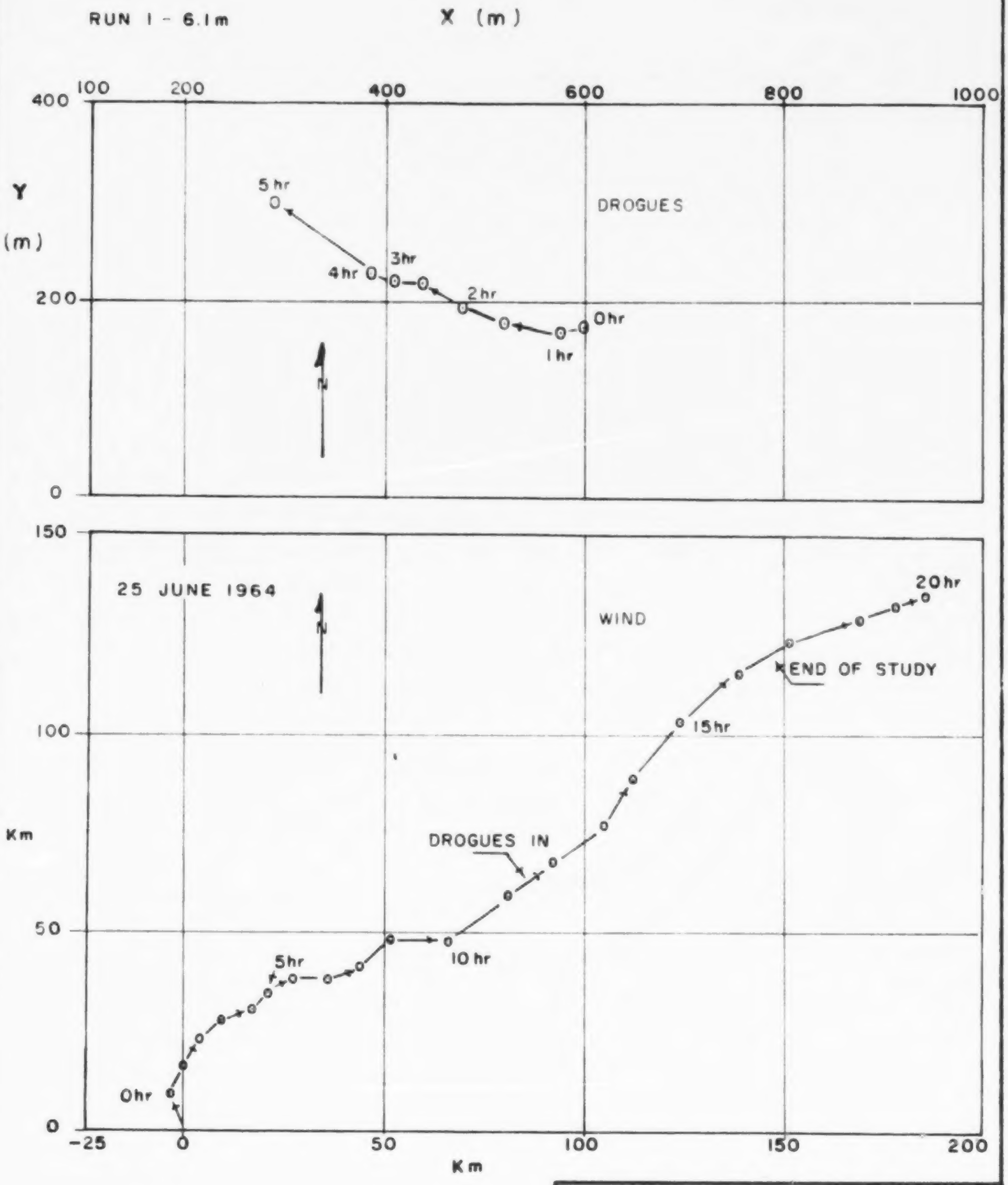
The movement of the center of mass of the drogues and the wind track on the day of experiment are shown in Figures 8-15 to 8-19. The wind data are available from airports near the studied area, each location being indicated on the field maps (Figures 8-4, 8-5, and 8-6). In general, the movement of the 1.5-m drogues may be interpreted as a result of the wind-driven current, the direction of which was somewhat to the right of the down-wind direction. On a change of wind the direction of the flow at 1.5 m changes within an hour or so. On the other hand, the movement of the 6.1-m drogues was generally against the local winds. In other words, the drogues at 1.5 and 6.1 m moved in directions opposed to one another. This implies that vertical shear in horizontal velocity did exist in the experimental area. Typical velocities at 1.5 and 6.1 m are estimated to be 4 and 2 cm/sec, respectively.

During the summer, a sharp thermocline develops at 5.4 to 6.1 m in the western part of Lake Erie. Thus the 6.1-m drogues were situated in or a little below the thermocline. The summer thermocline is usually not so conspicuous in southern Lake Michigan as in Lake Erie. The 6.1-m drogues in Lake Michigan were located below mid-depth, where a relatively weak stratification is present. The movement of the 1.5-m drogues should represent the flow in the surface layer, above 3.0 to 4.5 m.

The wind factor, the ratio between the current speed and the wind speed, is 0.008 at 1.5 m in Lake Michigan and in Lake Erie southeast of the Detroit River, but the factor in Lake Erie off Cleveland is about two times higher, i.e., 0.017. On the other hand, the wind factor at 6.1 m ranges between 0.005 and 0.008, the only exception to these values occurring in Lake Erie southeast of the Detroit River, where the drogues were set close to the bottom. On days with moderately strong, steady winds there should be a corresponding steady and uniform current in the surface layer, the direction of which is nearly parallel to the wind. The presence of boundaries should modify the current pattern; thus, close to the shoreline the mean current is nearly parallel to the shoreline even if the wind is offshore or onshore.

Characteristics of Diffusion

As previously mentioned, the standard deviations of the group of drogues do not necessarily reveal a regular pattern of turbulent dispersion. In the case where suppression or reversal of diffusion (apparently by convergence) is observed, no diffusion constants can be derived from the variation of standard deviations with time. Instead, the dispersion of drogues with respect to their initial position was computed for each of the eight groups of drogues. By doing so, we can regard the dispersion of drogues as if they were released consecutively from the same point, provided that the turbulent field is homogeneous

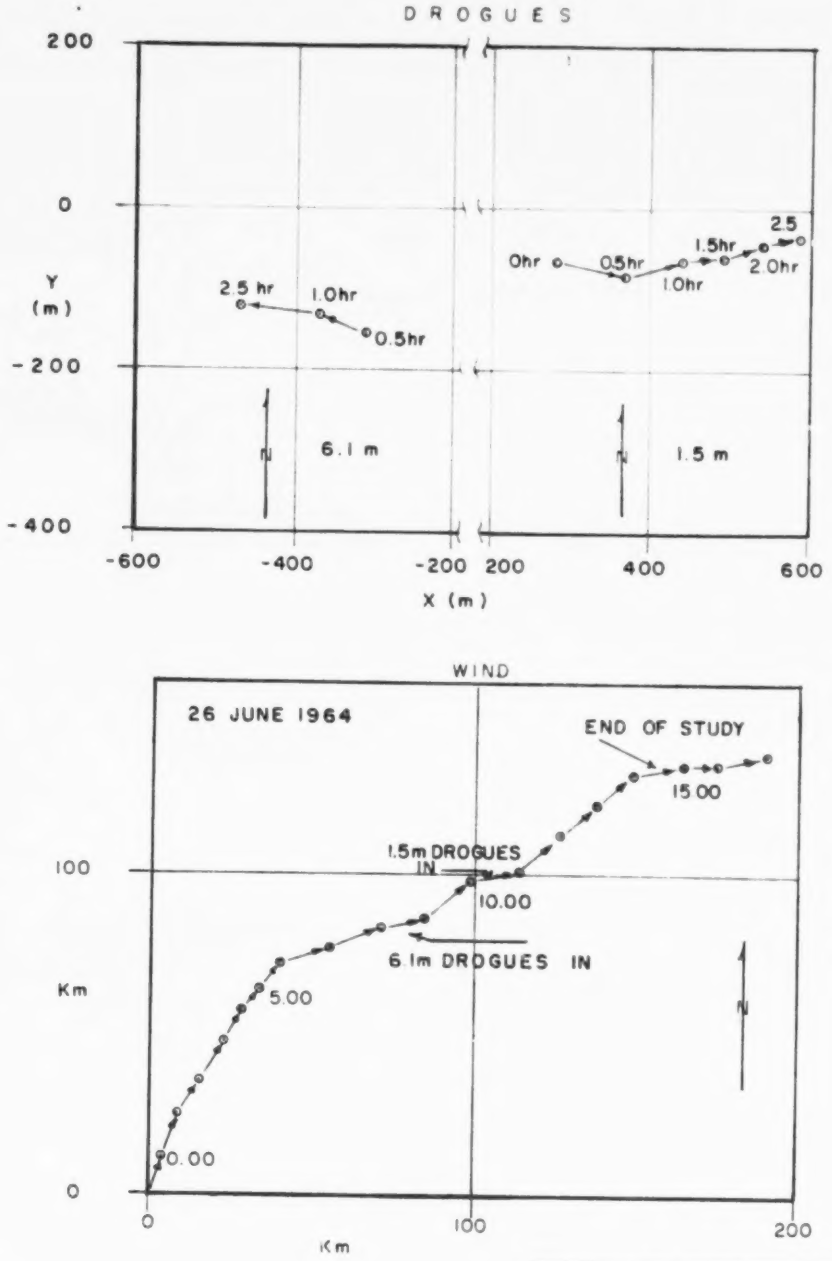


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

MOVEMENT OF DROGUES
& WIND TRACK
RUN I

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-15

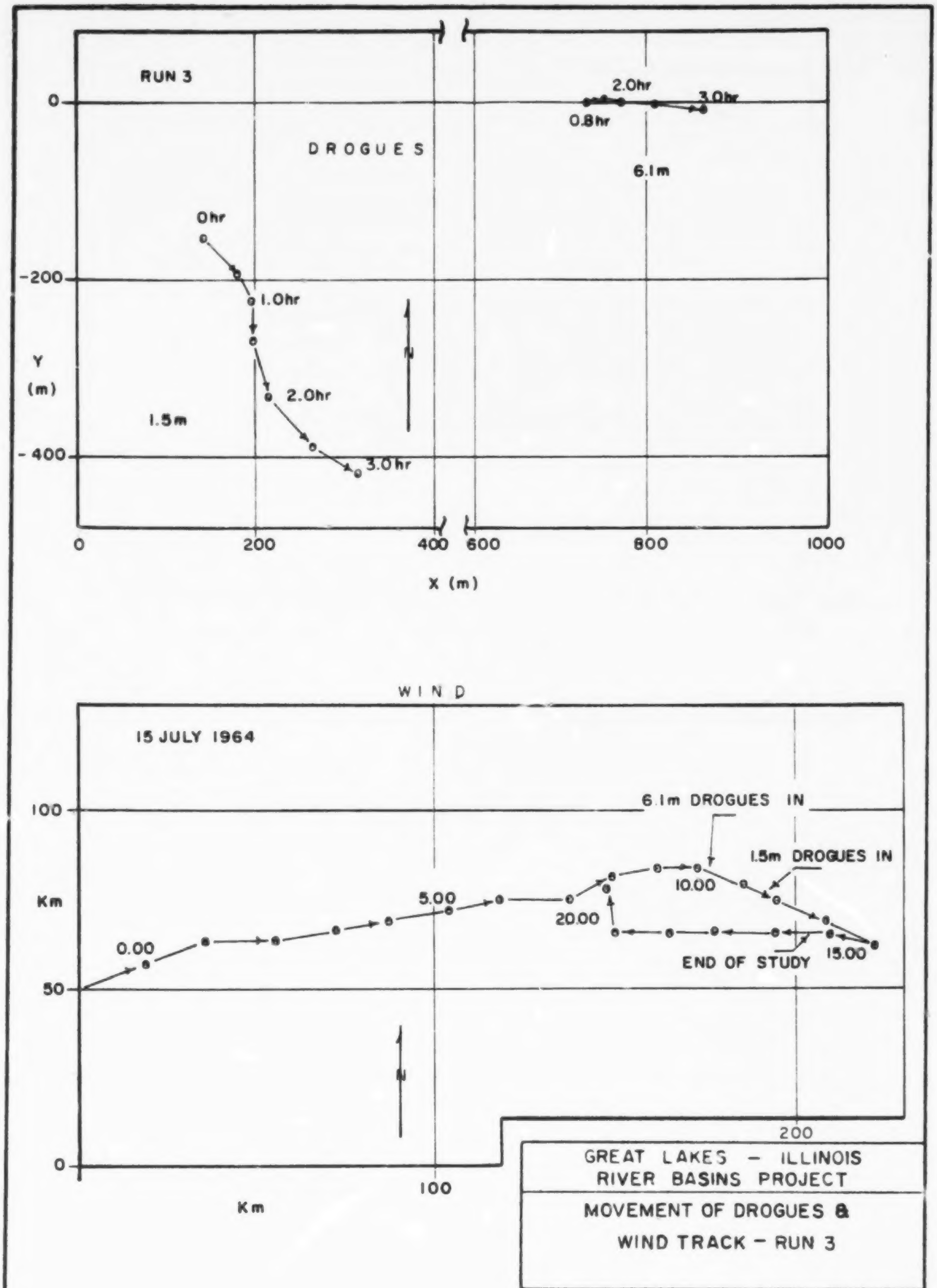


GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

MOVEMENT OF DROGUES
& WIND TRACK
RUN 2

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-16

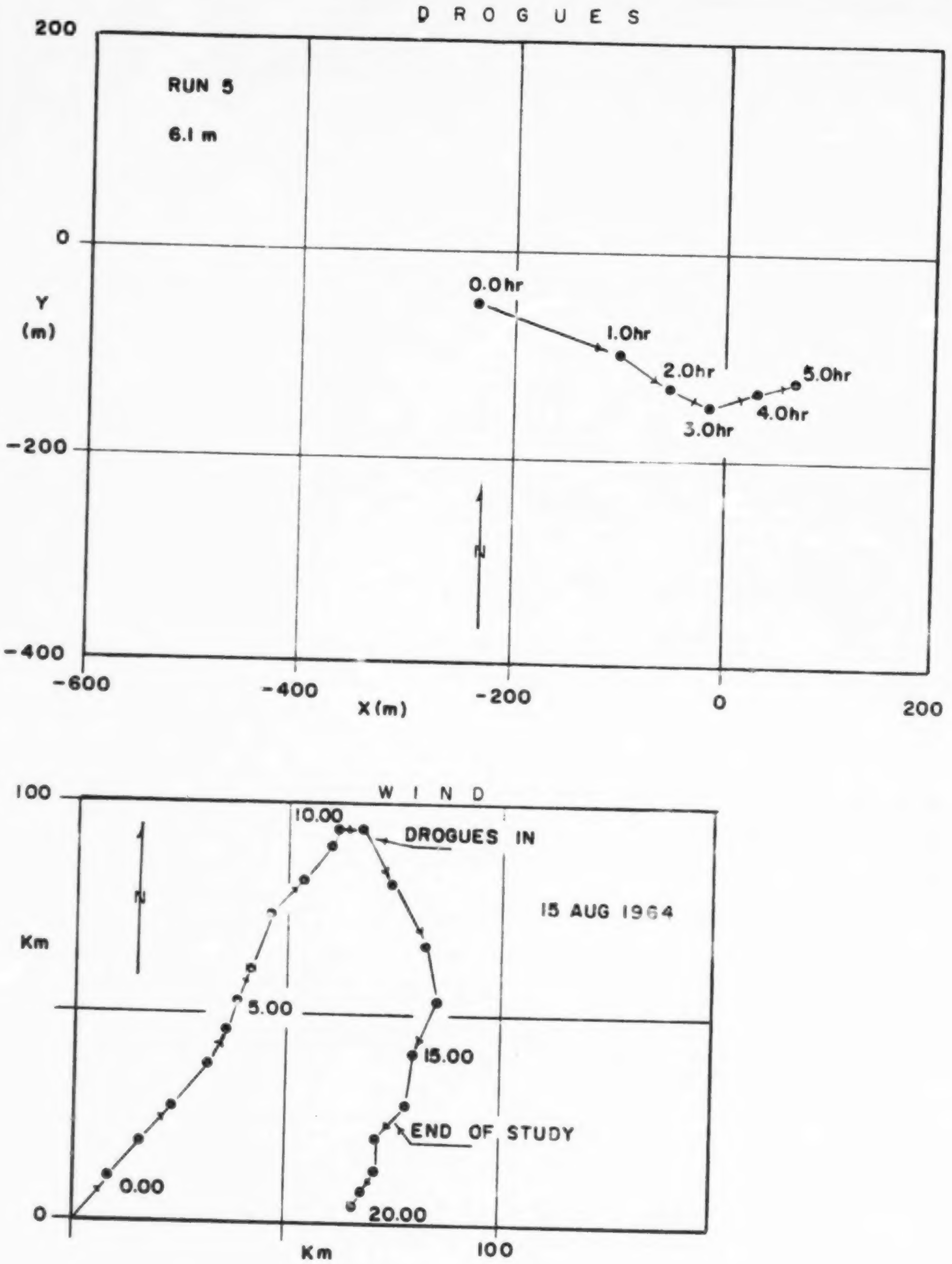


GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

MOVEMENT OF DROGUES &
WIND TRACK – RUN 3

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-17



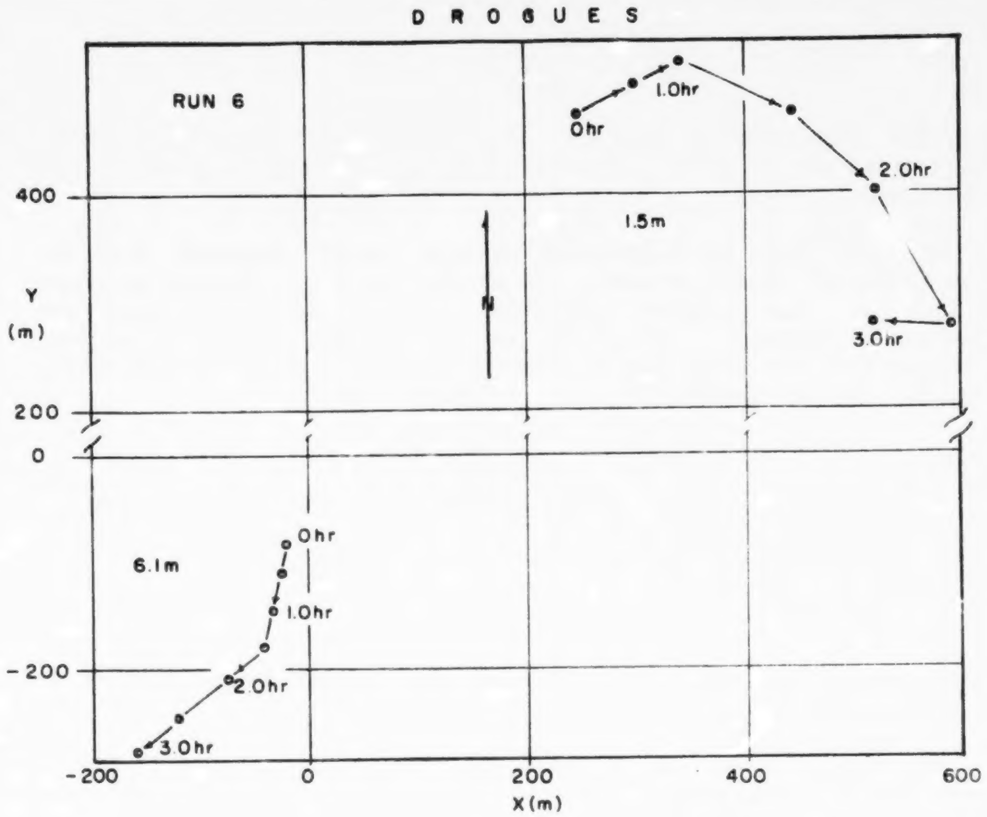
GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

MOVEMENT OF DROGUES
& WIND TRACK – RUN 5

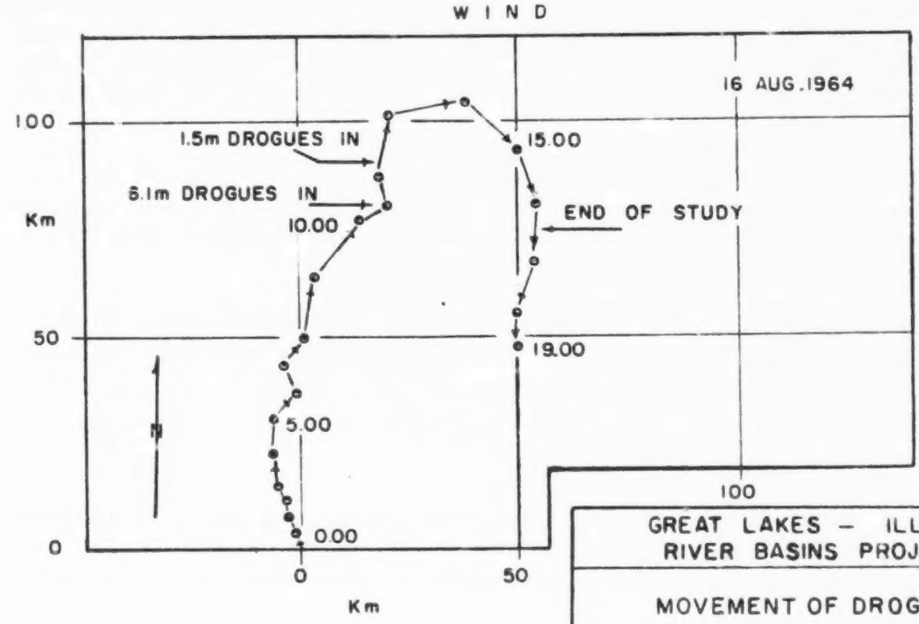
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-18

DROGUES



WIND



GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

MOVEMENT OF DROGUES
& WIND TRACK – RUN 6

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-19

(Hinze, 38). The adverse influence of convergences on the dispersion of the drogues may be partially eliminated in this manner. Figures 8-20 to 8-22 show the results.

When the scale of dispersion becomes large compared with the largest turbulent eddies present, its growth comes to resemble molecular diffusion, i.e., the standard deviation increases with the square root of time and a constant diffusivity can be defined. It is, of course, much larger than the molecular diffusivity. Thus, an effective diffusivity, K_e, may be computed from the formula

$$K_e = \frac{1}{2}\left(\frac{dD^2}{dt}\right)_{t \to \infty} , \qquad (1)$$

where D^2 denotes the variance of drogues at a time t with respect to their initial positions.

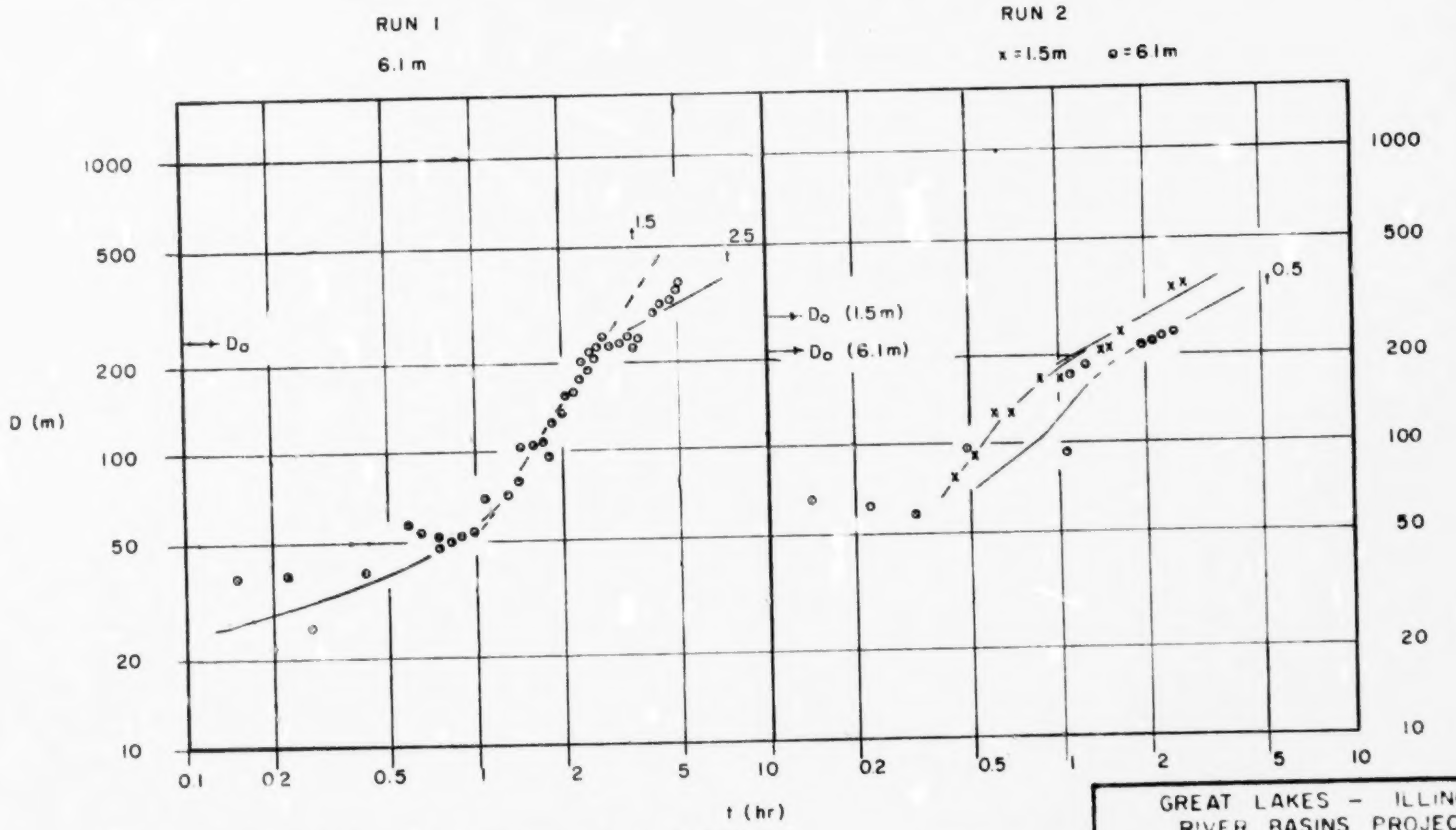
For the 1.5-m drogues in Run 6 and the 6.1-m drogues in Run 3, however, the $t^{\frac{1}{2}}$ relationship was not observed during the period of experiment (see Figures 8-21 and 8-22). Instead, a $t^{3/2}$ relationship characteristic of relative diffusion in homogeneous turbulence was present in the D^2-t diagrams. This behavior may suggest that the scale of the large eddies responsible for the horizontal dispersion of the drogues was not small in comparison with the group-size of drogues at the end of the experiment.

The values of K_e computed from (1) are shown in Table 8-2. All the values of the effective diffusivity lie in a relatively narrow range from 2.9×10^4 to 5.5×10^4 cm^2/sec, though slightly higher values are seen at 1.5 m.

The effective diffusivity may also be expressed as the product of v', the intensity of turbulence and L, the integral scale of turbulence (Hinze, 38):

$$K_e = v'L \quad . \qquad (2)$$

The scale L is a measure of the large-scale eddies and could be computed from knowledge of the Lagrangian velocity correlation. Since the Lagrangian correlations were unobtainable from the data, we must



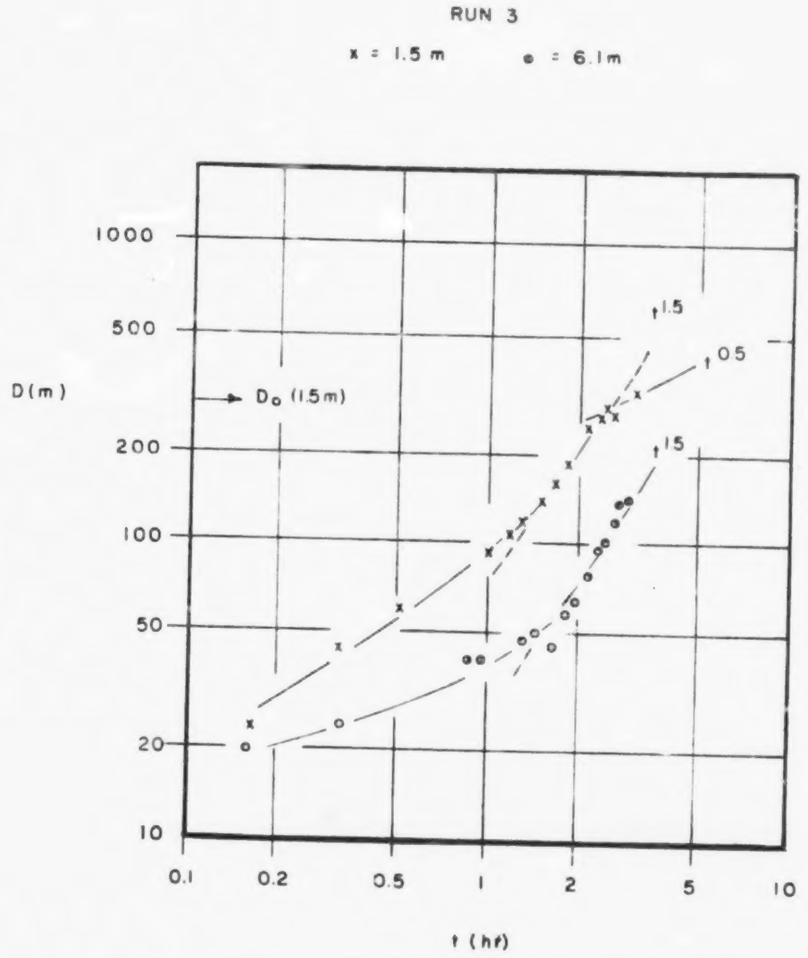
STANDARD DEVIATION OF DROGUES WITH RESPECT TO THEIR INITIAL POSITIONS VERSUS TIME

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMN
Great Lakes Region Chicago, Ill.

FIGURE 8-20



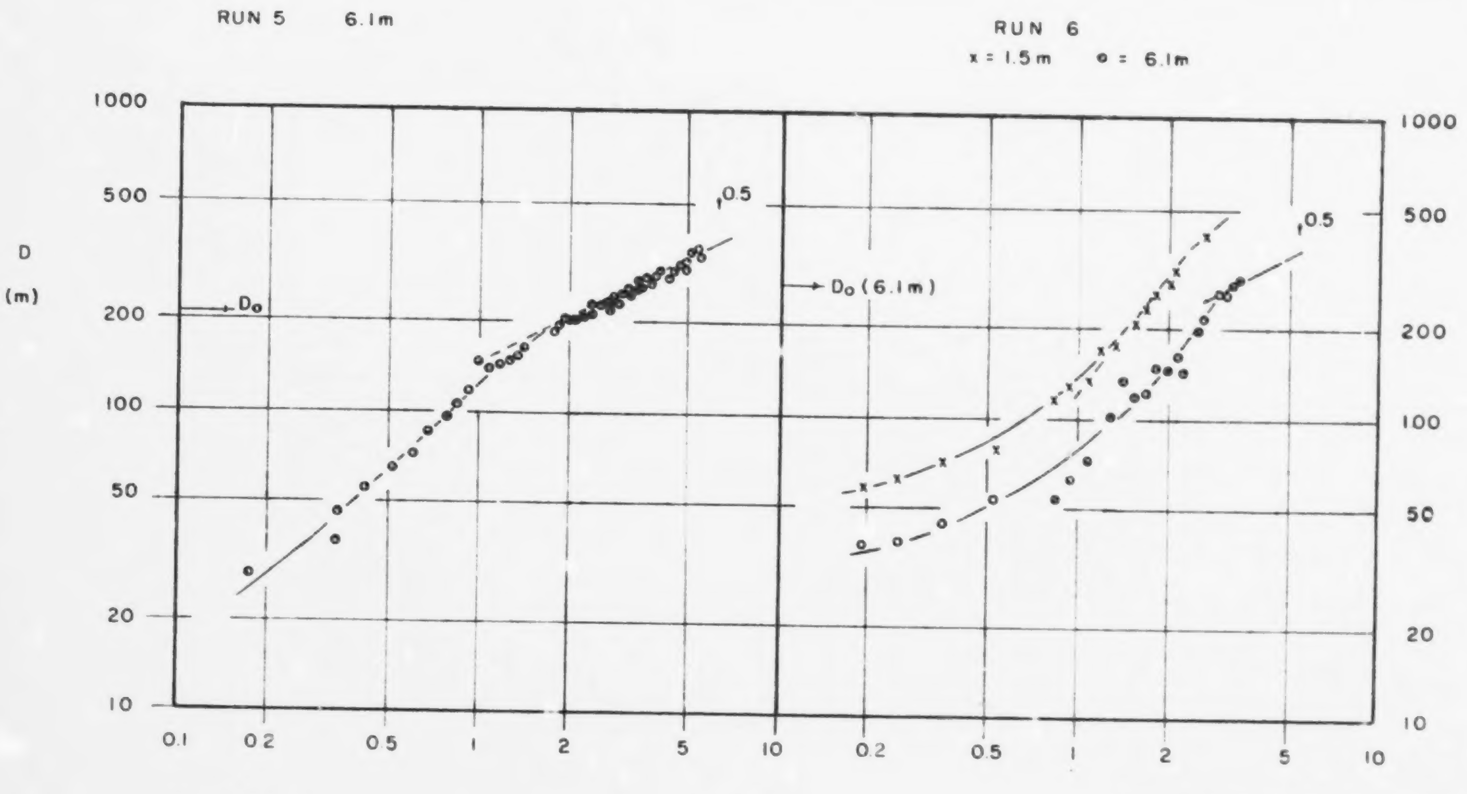
STANDARD DEVIATION OF DROGUES WITH RESPECT
TO THEIR INITIAL POSITIONS VERSUS TIME

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 8-21



STANDARD DEVIATION OF DROGUES WITH RESPECT TO THEIR INITIAL POSITIONS VERSUS TIME

GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

STANDARD DEVIATION

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-22

TABLE 8-2

VALUES OF CHARACTERISTICS OF DIFFUSION*

Run no.	Depth of drogues		Effective diffusivity	Intensity of turbulence	Rel. Int. of turbulence	Rate of Energy dissipation	Length of En.-cont. eddies(m)	Diffusion Velocity		$\frac{\omega}{U}$
	(m)	(ft)	K_e(cm^2/sec)	v'(cm/sec)	(%)	E(cm^2/sec^3)		ω (cm/sec)	P (cm/sec)	
1	**6.1**	20	2.9×10^4	0.33	11	3×10^{-4}	1	1.25	0.50	0.42
2	**1.5**	5	5.5×10^4	0.49	14	1×10^{-4}	12	0.8	0.32	0.24
	6.1	20	3.7×10^4	0.44	20	1×10^{-4}	9	0.65	0.26	0.29
3	**1.5**	5	4.1×10^4	0.35	11	2×10^{-4}	3	1.2	0.48	0.39
	6.1	20				8×10^{-5}		0.4	0.16	0.25
5	**6.1**	20	3.2×10^4	0.38	19	3×10^{-5}	3	0.55	0.22	0.28
6	**1.5**	5				4×10^{-4}		1.6	0.64	0.27
	6.1	20	3.3×10^4	0.30	10	4×10^{-5}	7	0.25	0.10	0.08

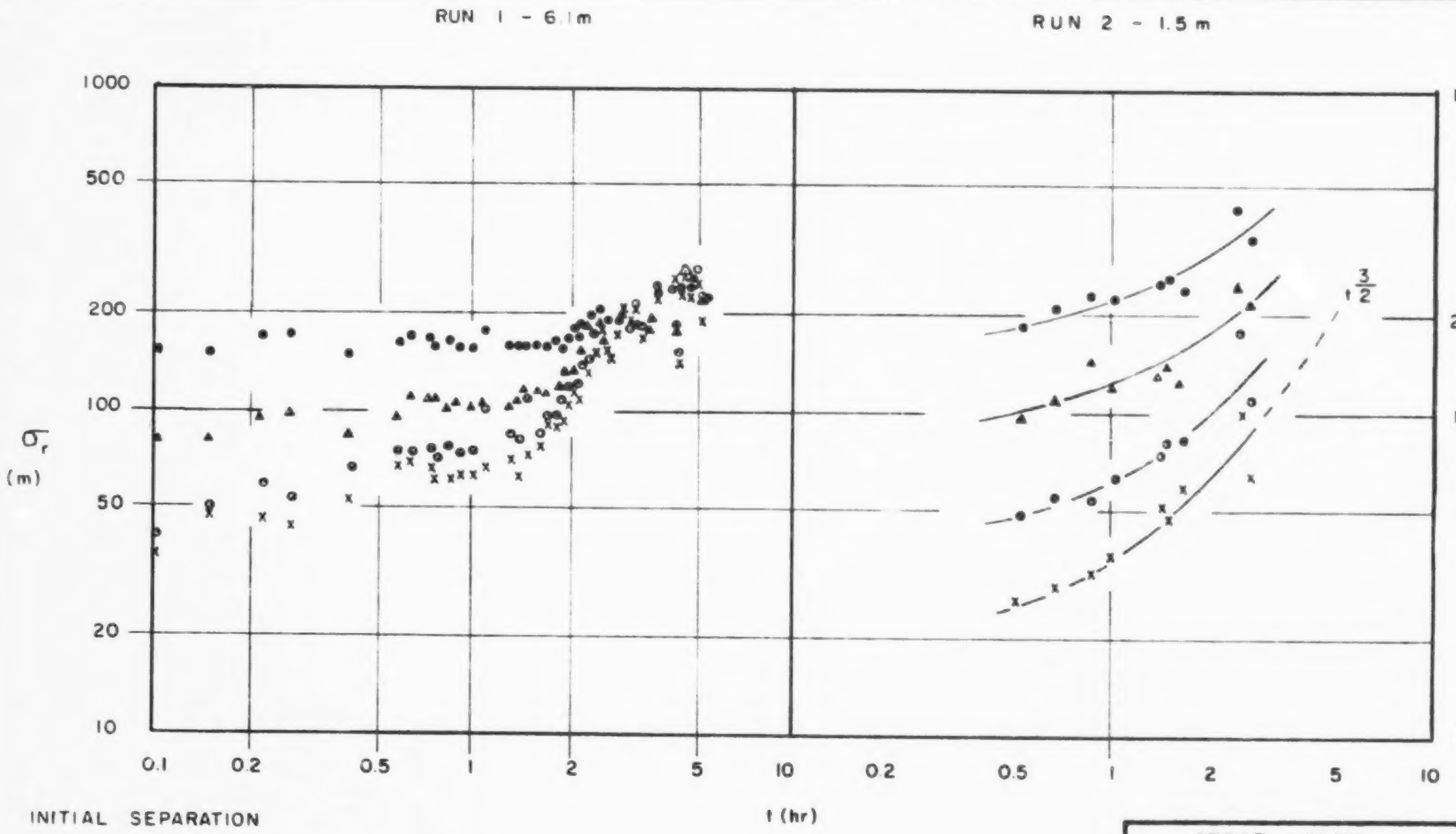
***See text for definitions.**

estimate L by another method. As previously pointed out, D versus t exhibits an asymptotic behavior when the scale of diffusion becomes larger than L. Accordingly, the length-scale L may be obtained approximately from the D-t diagram as follows. D_o, which is the lowest value of D for which D is proportional to $t^{\frac{1}{2}}$, is determined from the D versus t figures. Provided the distribution of drogues is gaussian, a characteristic length-scale of distribution may be given by 4 D_o; that is, approximately 95 percent of the drogues will be found within the distance ± 2 D_o from the mean of the distribution. Hence, we take $L = 4\ D_o$.

Having obtained the values of K_e and L, we are now able to compute v' by (2). The results are summarized in Table 8-2. The intensity of turbulence differs very little between Lake Michigan and Lake Erie and also between the depths of 1.5 and 6.1 m. This is primarily due to the fact that the mean velocity was nearly identical except at 1.5 m in Run 6, for which no estimate of intensity of turbulence was given because of the lack of an asymptotic relationship between D^2 and t. The relative intensity of turbulence, the ratio between the intensity of turbulence and the mean velocity, is also computed (see Table 8-2). The values range from 10 to 20 percent.

One way of treating relative diffusion is to observe the rate of increase of mean separation of a pair of drogues with the same initial separation, ℓ_o. Figures 8-23 to 8-26 show the root-mean-square separations versus time for various initial separations. For small initial separations, the root-mean-square separations increase regularly with time even in the case where the group of drogues encountered converges so that suppression or reversal of dispersion occurred. Small-scale turbulent motions allow a pair of drogues with small separations to diffuse regularly, provided that the characteristic scale associated with the convergences or divergences is large compared with the separation of the drogues. On the other hand, the effect of the convergences on dispersion is marked for a pair of drogues having large initial separations. Apparently the large-scale convergences prohibit the drogues from diffusing regularly. The results of the pair-program suggest that the scale of the convergences was on the order of 100 meters.

A theoretical treatment of this relative diffusion, presumably valid for the ideal case of homogeneous turbulence and uniform mean flow has been developed by Batchelor (4). Dimensional arguments on the basis of similarity theory of turbulence are applied to three regimes of relative dispersion. These regimes are characterized by the following behaviors with time of the mean square separations of a pair of drogues which start with a same initial separation, ℓ_o:



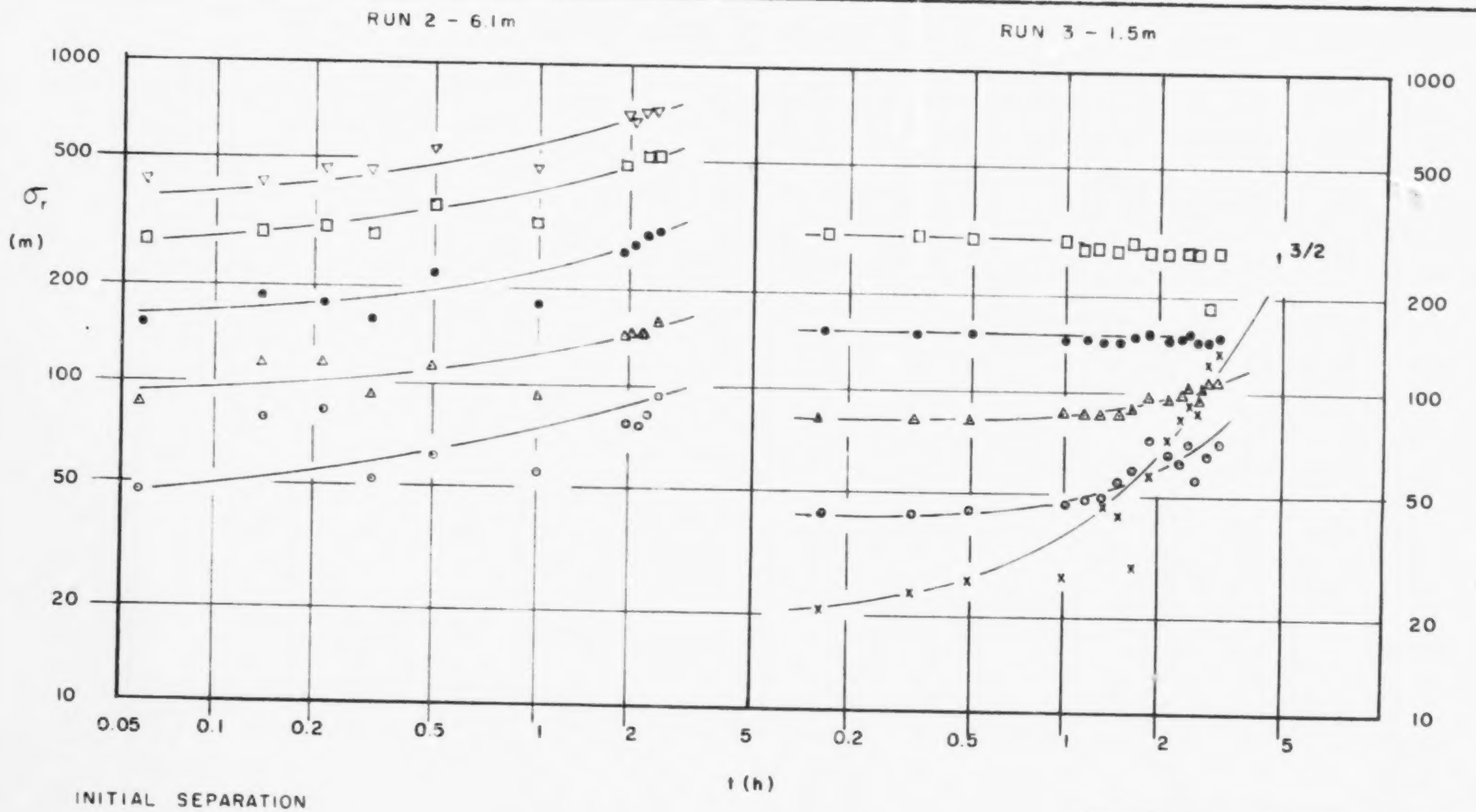
MEAN SEPARATION OF A PAIR OF DROGUES VERSUS TIME

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

MEAN SEPARATION

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-23



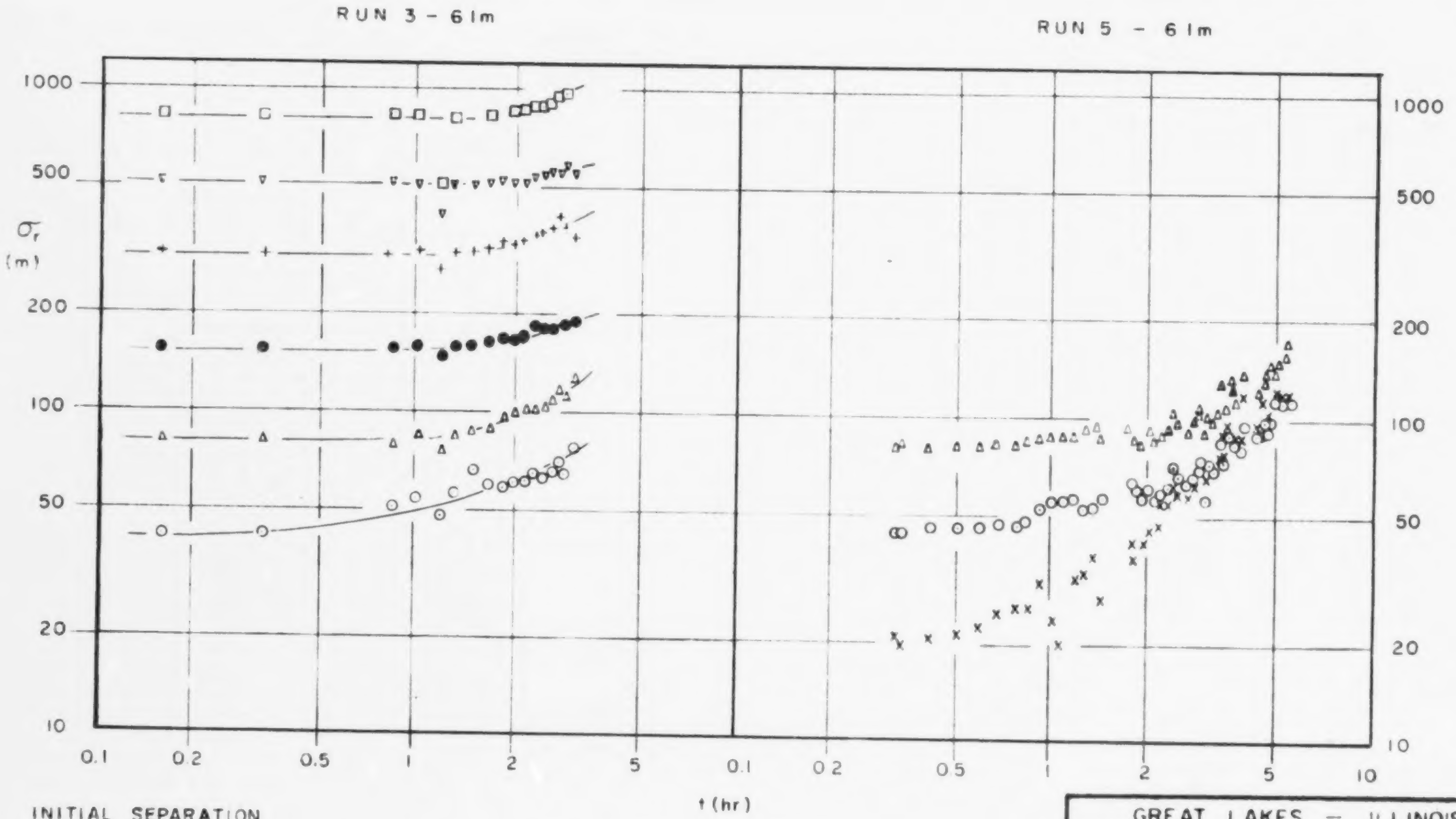
MEAN SEPARATION OF A PAIR OF DROGUES VERSUS TIME

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

MEAN SEPARATION

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region [illegible]

FIGURE 8 - 24



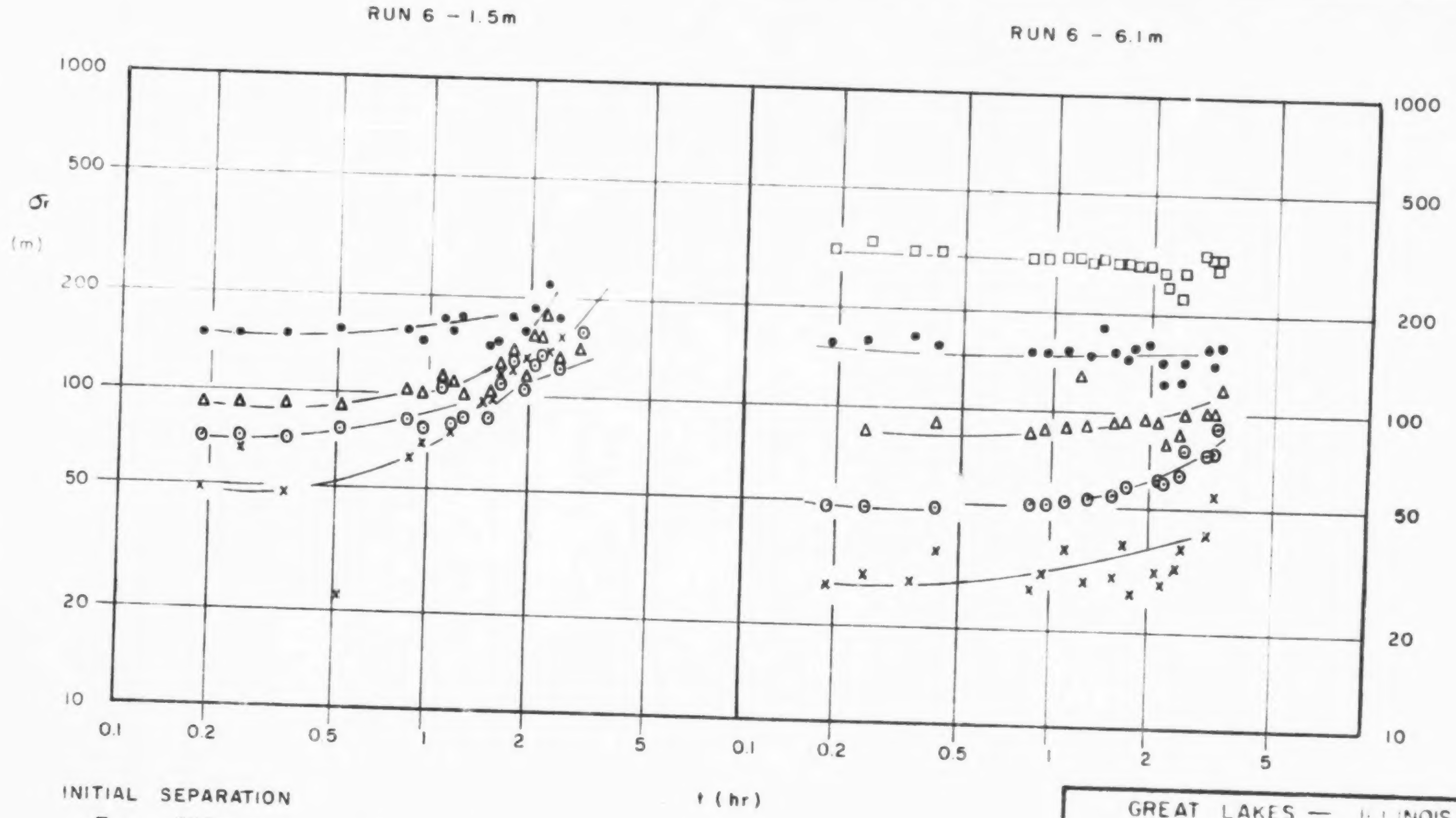
MEAN SEPARATION OF A PAIR OF DROGUES VERSUS TIME

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

MEAN SEPARATION

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-25



MEAN SEPARATION OF A PAIR OF DROGUES VERSUS TIME

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

MEAN SEPARATION

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-26

$$\sigma_r^{\,2} = \ell_0^{\,2} + c_1(E\ell_0)^{2/3}\, t^2 \quad , \quad t \ll t_1 \sim \ell_0^{\,2/3}\, E^{-1/3} \quad \text{(initial)} \tag{3}$$

$$\sigma_r^{\,2} = c_2\, E\, t^3 \quad , \quad t \gg t_1 \quad \text{(intermediate)} \tag{4}$$

$$\sigma_r^{\,2} \propto t \quad , \quad t \to \infty \quad \text{(asymptotic)} \tag{5}$$

Here c_1 and c_2 are constants of order unity, $\sigma_r^{\,2}$ is the mean square separation of a pair of drogues, E is the rate of energy-dissipation per unit mass through turbulence. For E the following relationship is also noted (Batchelor, 5):

$$E = v'^3/L^*, \tag{6}$$

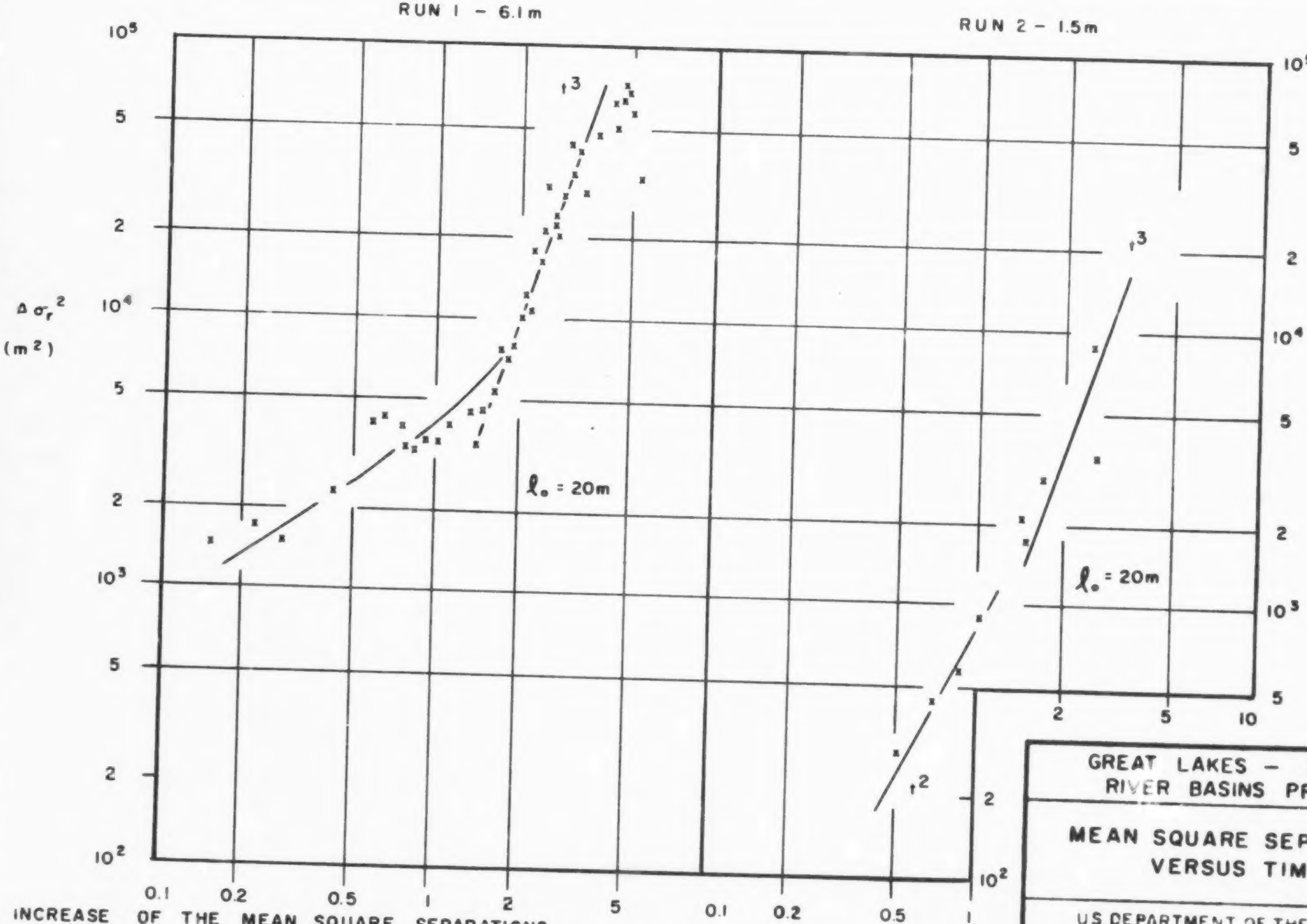
with v' the intensity of turbulence and L* the length scale of the energy-containing eddies.

Figures 8-27 to 8-30 illustrate the time behaviors of the increase of the mean square separations for some typical cases. The Figures show that, in regular diffusion, the t^3-relationship predicted by the theory for the intermediate regime is easily recognizable, in spite of the expected statistical scatter.

The rate of energy dissipation may be evaluated for the intermediate phase by application of equation (4). Numerical values extracted from the results are summarized in Table 8-2. At 1.5-m depth, the order of magnitude of the energy dissipation is the same for the two Lakes, typical values being 2×10^{-4} cm^2/sec^3. On the other hand, at 6.1 m, the rate of energy dissipation was higher by approximately an order of magnitude in Lake Michigan, typical values being 2×10^{-4} cm^2/sec^3 for Lake Michigan and 4×10^{-5} cm^2/sec^3 for Lake Erie.

The length scale of the energy-containing eddies can be computed for the case where both values of E and v' are available. Table 8-2 summarizes the results. A mean value of the scale of the energy-containing eddies is several meters in both Lakes.

Theoretical treatments of the concentration distribution from an instantaneous source in the sea have been developed (see papers reviewed



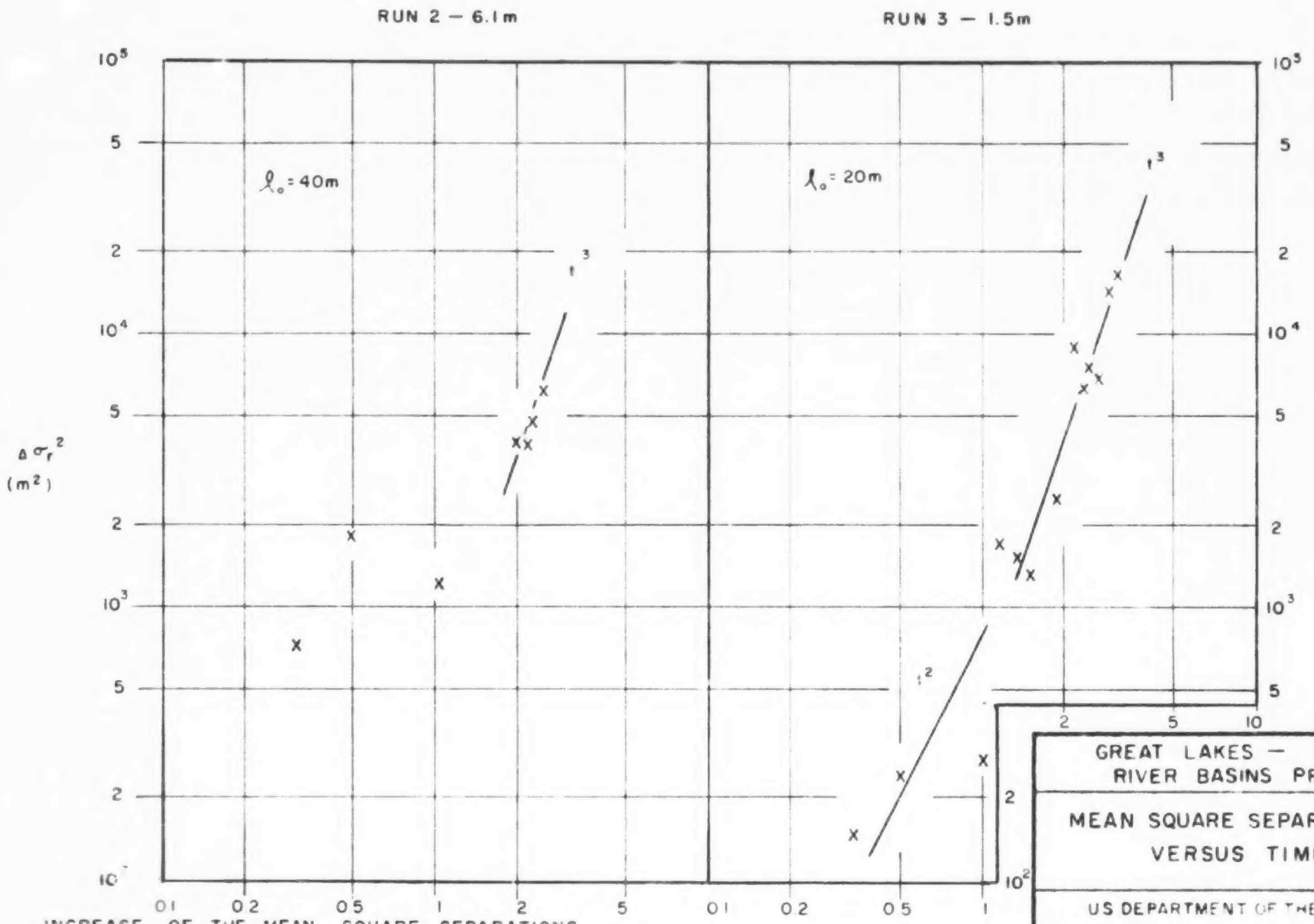
INCREASE OF THE MEAN SQUARE SEPARATIONS VERSUS TIME

GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

MEAN SQUARE SEPARATION VERSUS TIME

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-27



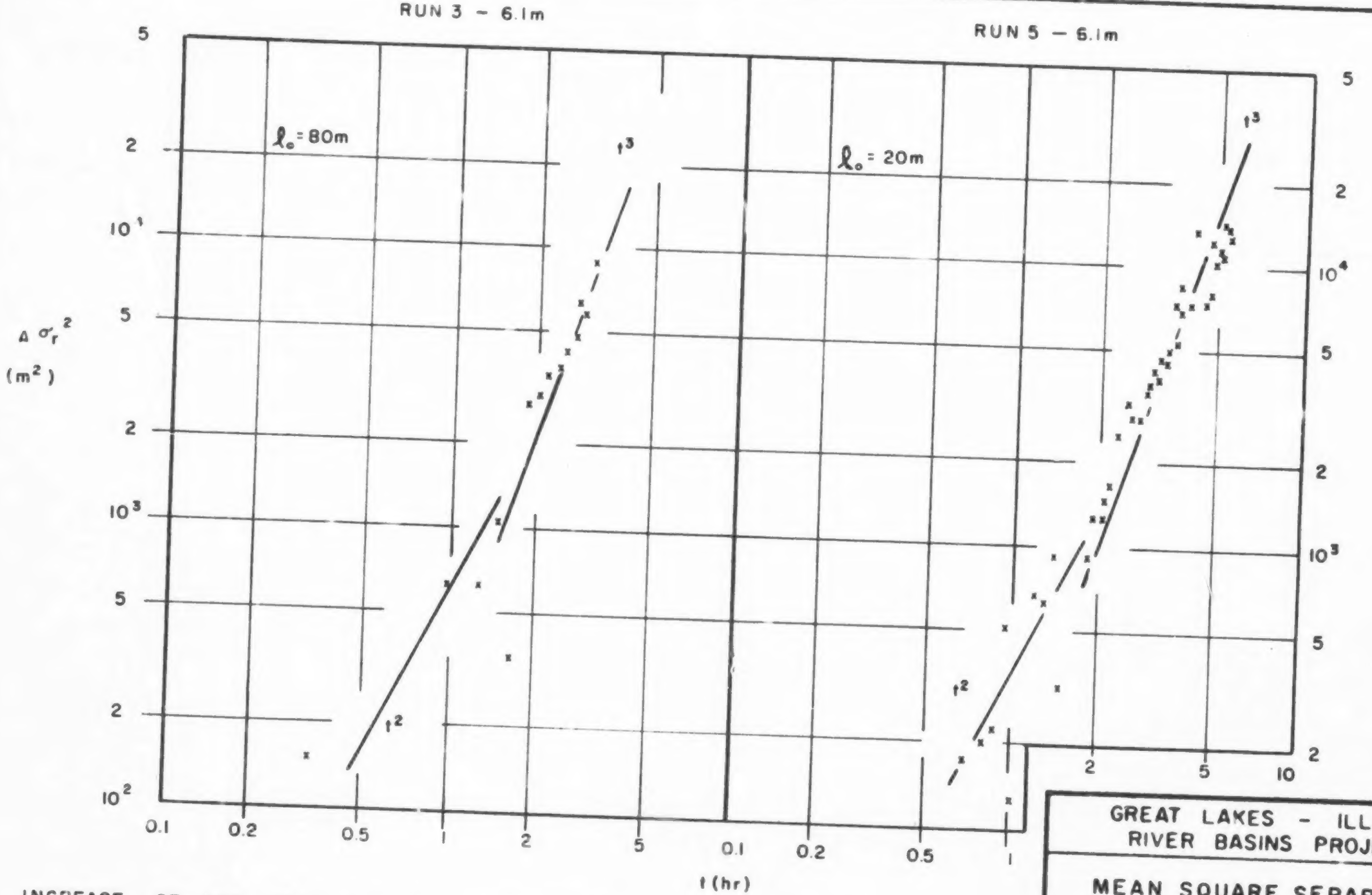
INCREASE OF THE MEAN SQUARE SEPARATIONS VERSUS TIME

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

MEAN SQUARE SEPARATION
VERSUS TIME

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-28



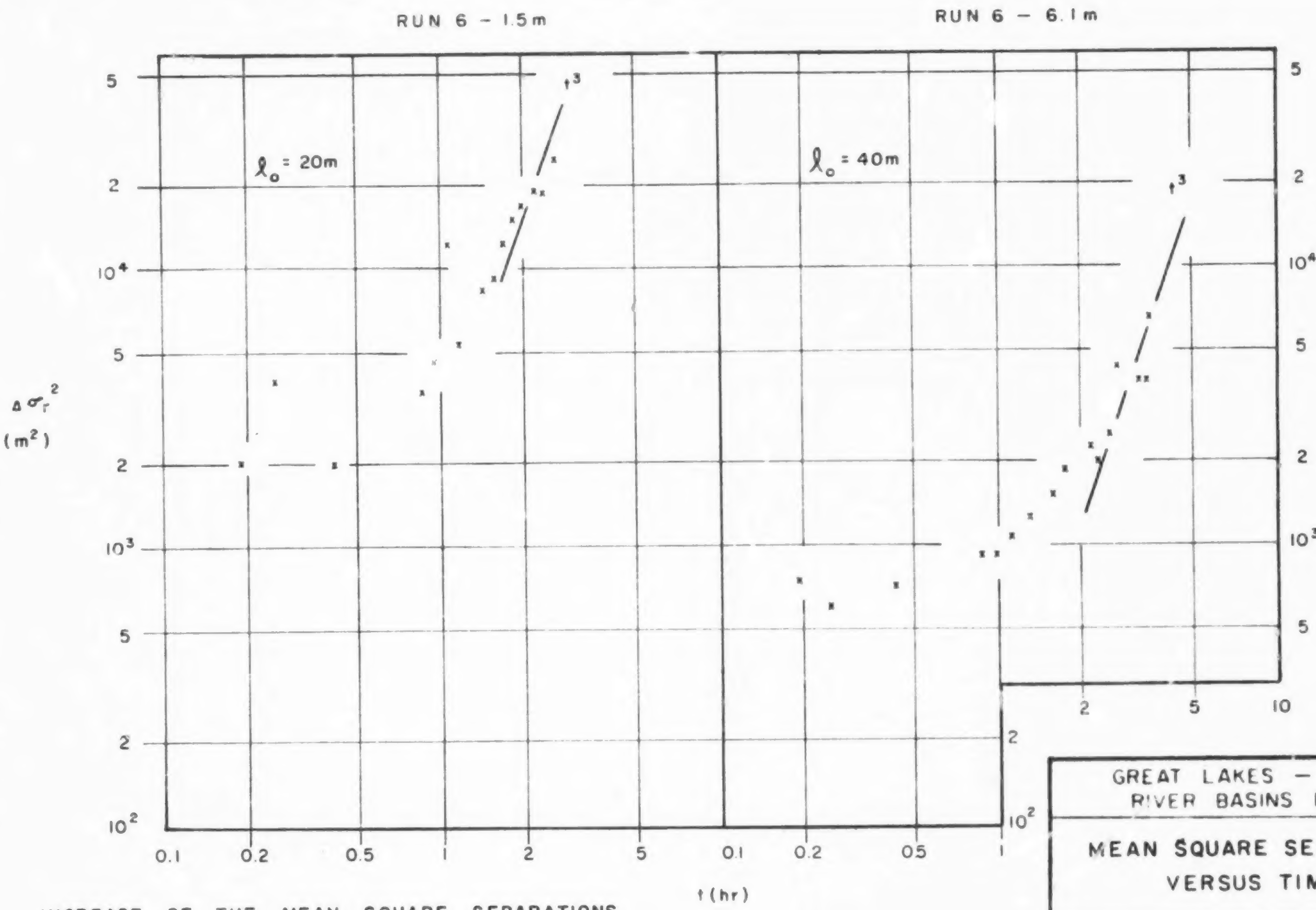
GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

MEAN SQUARE SEPARATION
VERSUS TIME

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

INCREASE OF THE MEAN SQUARE SEPARATIONS VERSUS TIME

FIGURE 8-29



INCREASE OF THE MEAN SQUARE SEPARATIONS VERSUS TIME

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

MEAN SQUARE SEPARATION
VERSUS TIME

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-30

by Okubo (5) and Bowden (12). Horizontal dispersion of drogues in a lake should also be described by those theories with minor modifications, among which either Joseph and Sendner's theory (46) or Okubo and Pritchard's theory (58) is a satisfactory model for our purposes.

Both theories predict the temporal behavior of the standard deviation of the distribution from a point-source as

$$\sigma_r = \omega t \tag{7}$$

$$= \sqrt{6}\, Pt \quad , \tag{8}$$

where ω and P represent a diffusion velocity in Joseph-Sendner's theory and Okubo-Pritchard's theory, respectively. For dispersion of drogues with a finite initial separation, however, equations (7) and (8) should be modified as

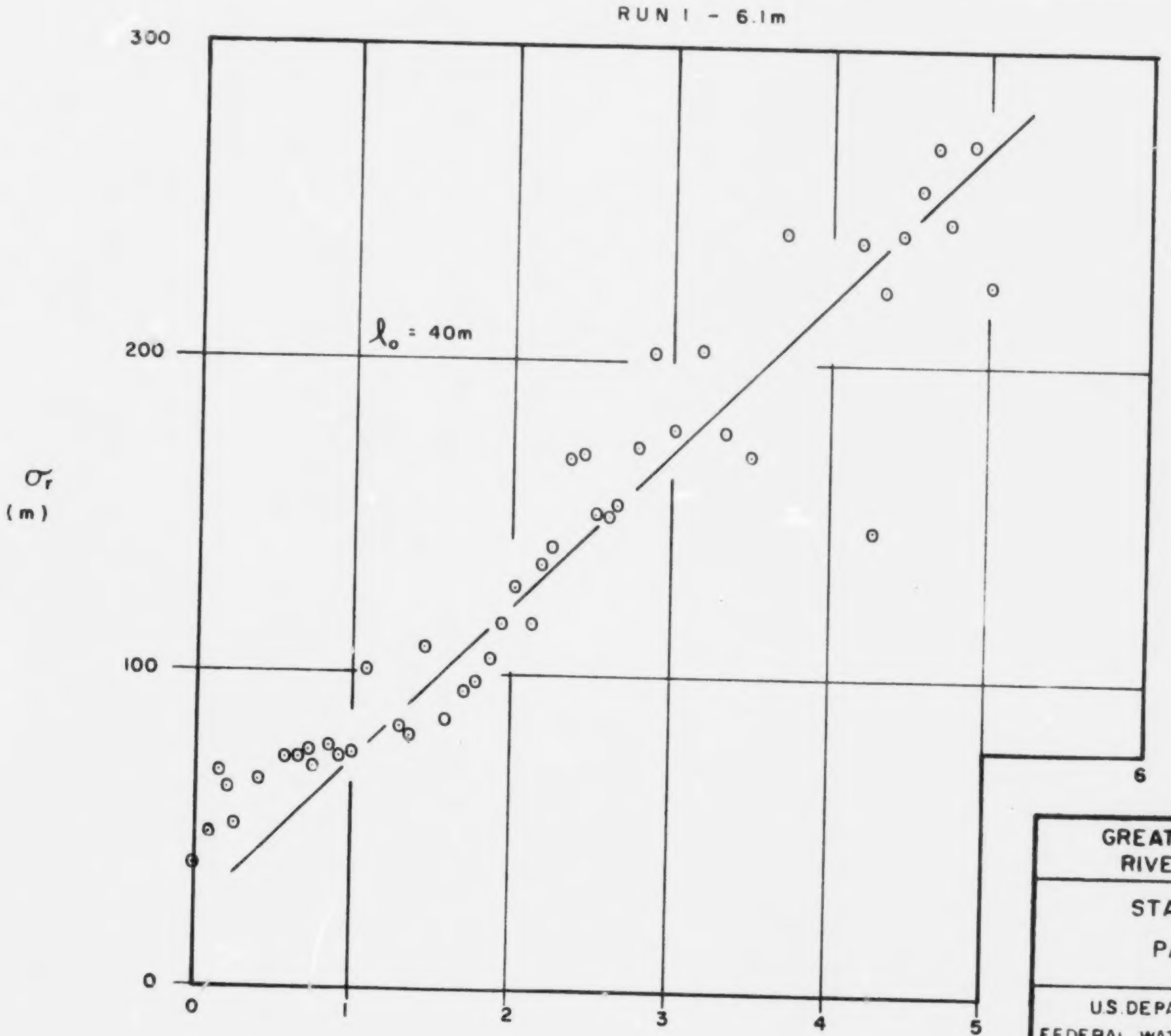
$$\sigma_r = \omega\,(t + t_0) \tag{9}$$

$$= \sqrt{6}\, P\,(t + t_0) \quad . \tag{10}$$

where t_0 is defined to be a fictitious time at which we regard the group of drogues as concentrated at a point.

Figures 8-31 to 8-35 show the standard deviations versus time for a pair of drogues starting with the same separations. In each Figure we also draw a theoretical line to fit the data points, so that the values of ω and P may be obtained. The results are shown in Table 8-2.

According to theory, the diffusion velocity is a measure of intensity of turbulent diffusion. Thus the turbulent diffusion in the surface layer, say at 1.5 m, seems to be more intense in Lake Erie than in Lake Michigan; but in the deeper layer, say at 6.1 m, the diffusion velocity in Lake Michigan was higher than that of Lake Erie. In the sea, for comparison, the diffusion velocity ω ranges from 0.7 to 2.5 cm/sec (58) while Pritchard and Carpenter (60) found ω = 0.2 cm/sec in Conowingo Reservoir.



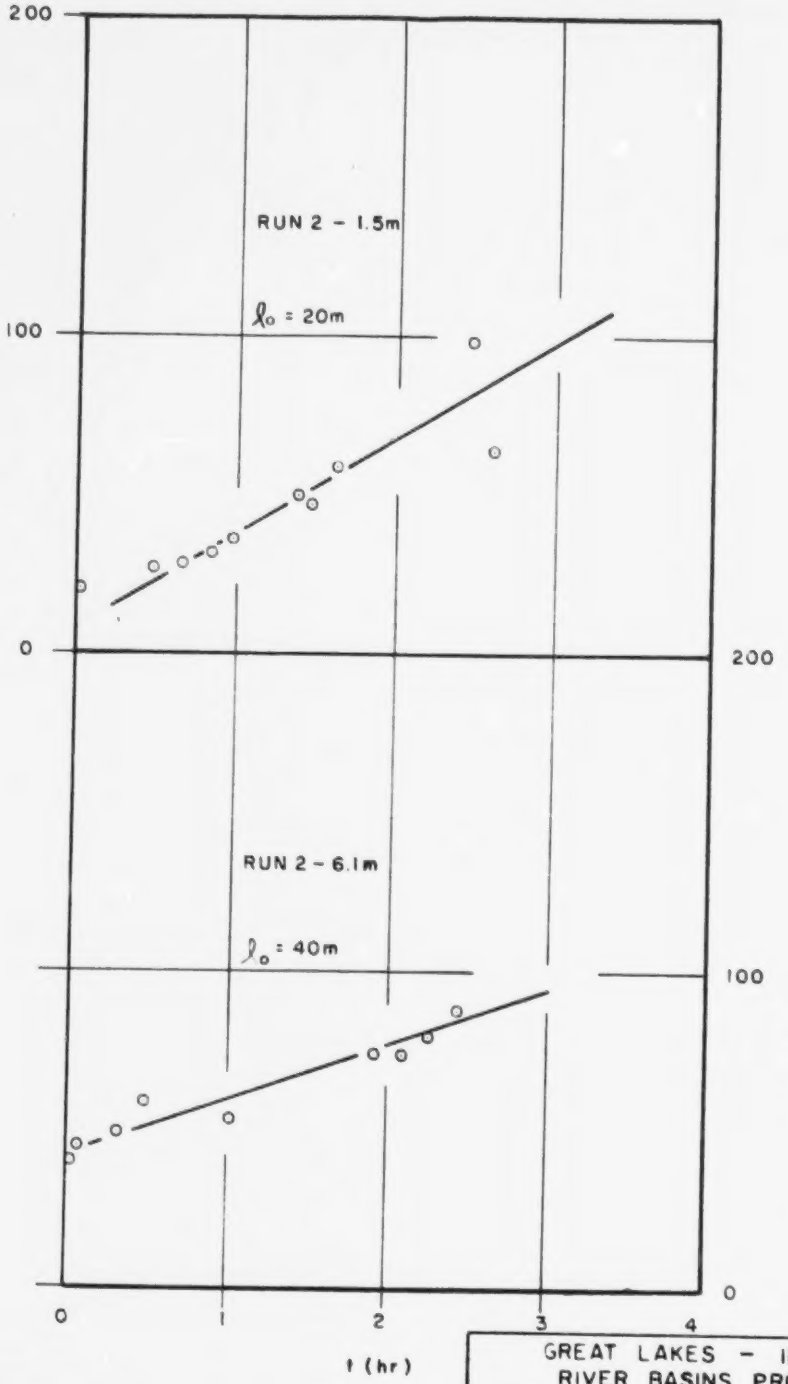
STANDARD DEVIATION OF A
PAIR OF DROGUES VERSUS
TIME

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION
PAIR VERSUS TIME

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-31



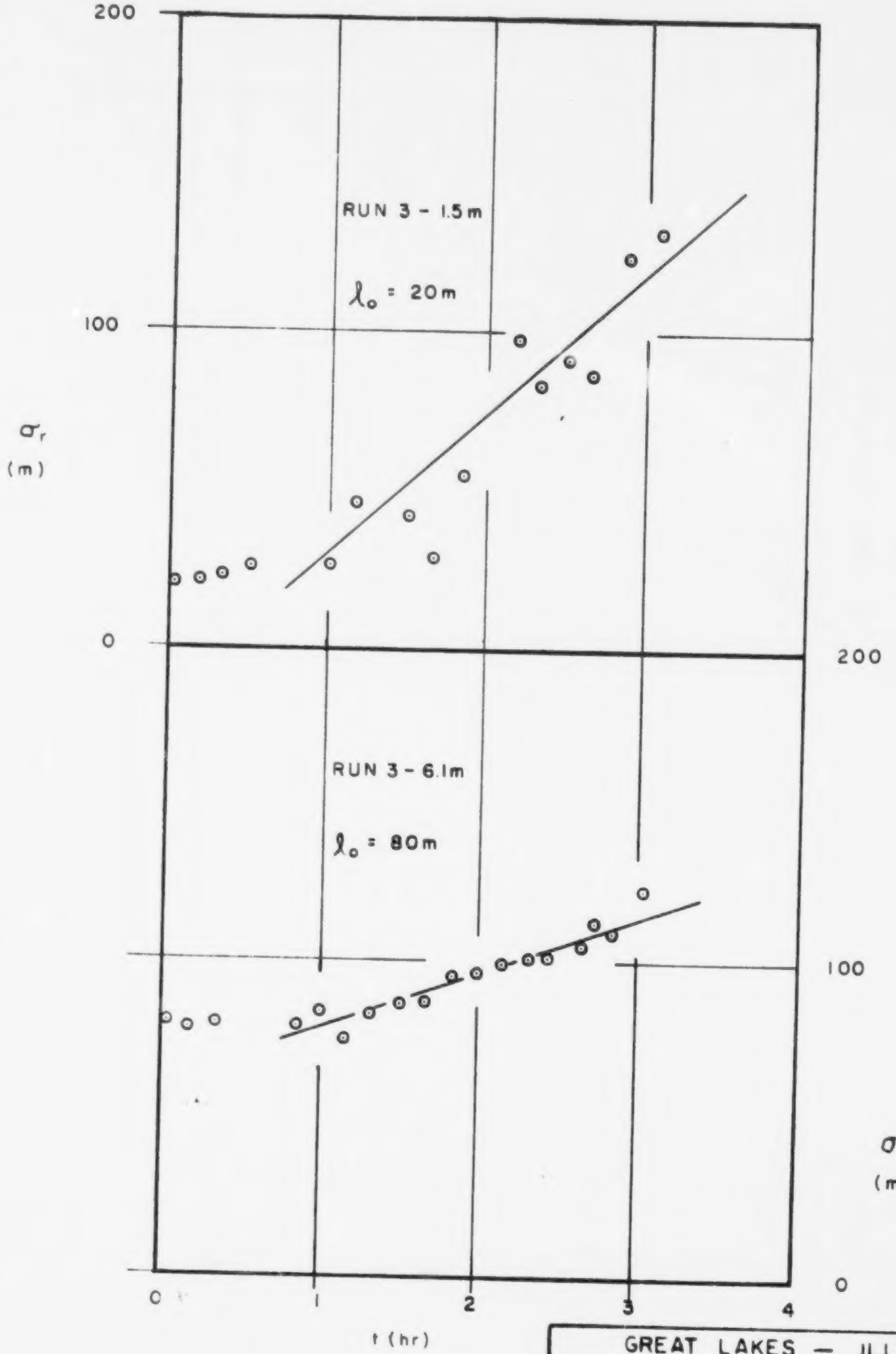
STANDARD DEVIATION OF A PAIR OF
DROGUES VERSUS TIME

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION
PAIR VERSUS TIME

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

GURE 8-32



STANDARD DEVIATION OF A PAIR OF DROGUES VERSUS TIME

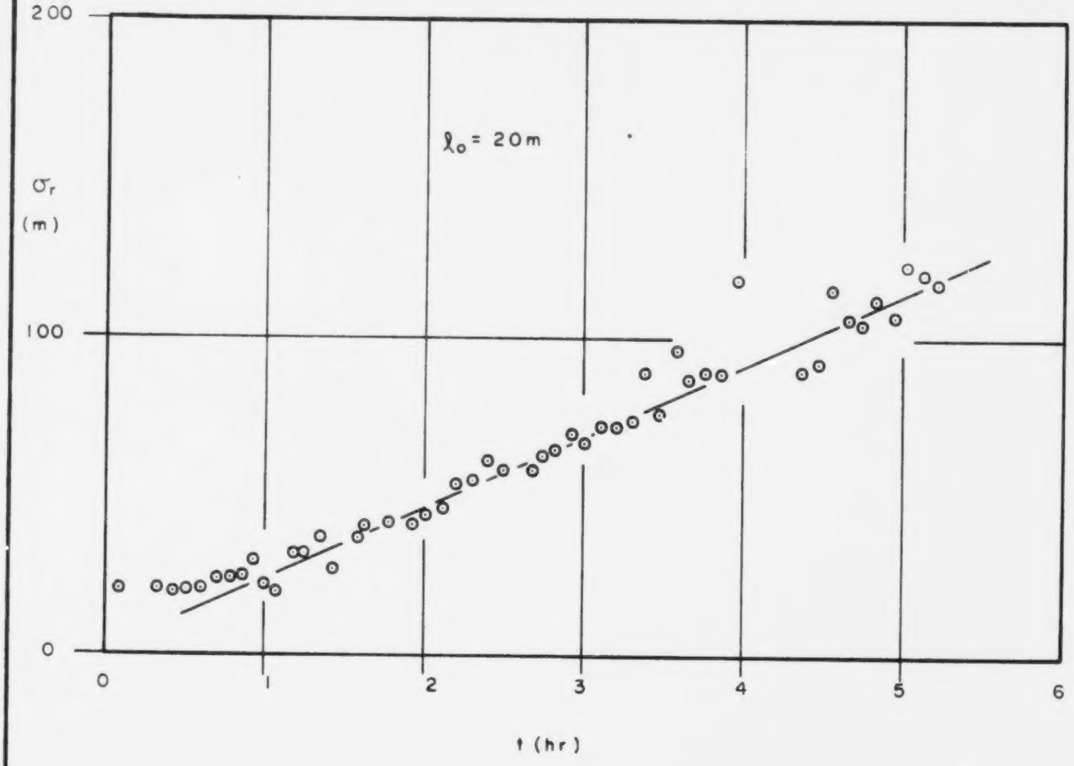
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION
PAIR VERSUS TIME

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-33

RUN 5 - 6.1m



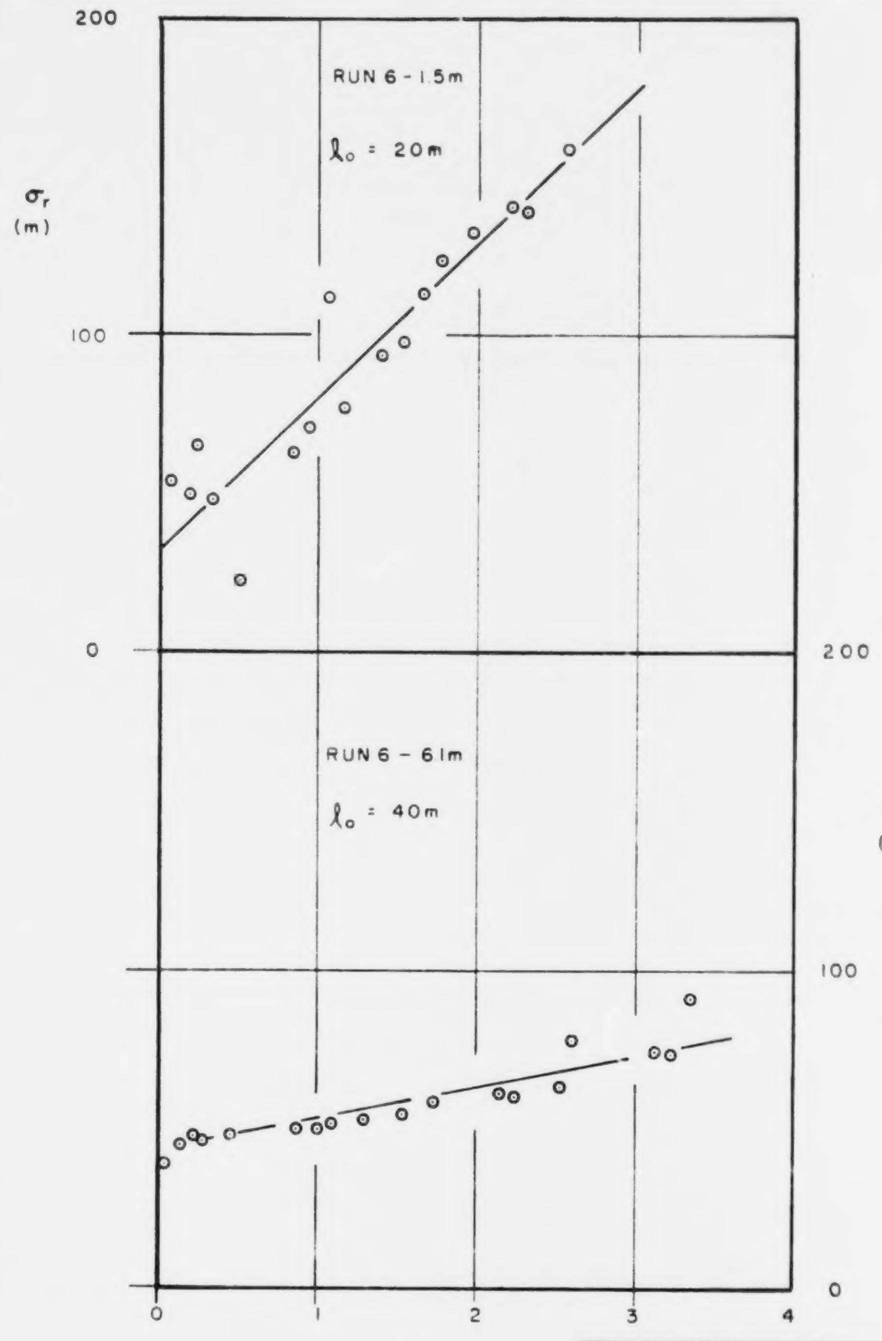
STANDARD DEVIATION OF A PAIR OF DROGUES VERSUS TIME

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION
PAIR VERSUS TIME

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 8-34



STANDARD DEVIATION OF A PAIR OF DROGUES VERSUS TIME

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

STANDARD DEVIATION
PAIR VERSUS TIME

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-35

Noble (56) measured the rate of dilution of a dye patch in the surface water of Little Traverse Bay of Lake Michigan. A Joseph-Sendner diffusion velocity of 0.3 cm/sec was selected to obtain a good fit to the experimental data. The value is in good agreement with the value at 1.5 m obtained in the drogue study in Lake Michigan.

Csanady (22) studied the dispersion of small floating objects and of fluorescent dye in Lake Huron at Douglas Point. The scale of energy-containing eddies was consistently on the order of 10 meters, ranging from 4 to 20 meters, which is slightly larger than that obtained in the drogue studies, while an order of magnitude estimate for the intensity of turbulence was 0.5 to 0.7 cm/sec in the surface layer, which should be compared with the values 0.4 to 0.5 cm/sec obtained at 1.5 m in the drogue studies. By using Csanady's data, we can compute the rate of energy-dissipation from equation (6). The result shows that, in spite of a wide scatter of individual values ranging from 1×10^{-5} to 6×10^{-4} cm^2/sec^3, the average value of E takes 3.5×10^{-4} cm^2/sec^3, which is quite consistent with the value of E at 1.5-m depth obtained in the drogue studies.

Csanady (23) also studied diffusion of fluorescent dye from a continuous source in the western basin of Lake Erie. Two measured diffusivities were 2.6×10^3 and 4.4×10^3 cm^2/sec in August. These values are very small compared with those obtained in the drogue studies. If we accept a well-known law that the apparent diffusivity is proportional to the 4/3 power of the scale (Richardson, 63) Csanady's values would be close to the values of the drogue studies; thus Csanady's values would correspond to 1.7×10^4 and 2.8×10^4 cm^2/sec for a scale of 240 meters (D_o estimated to be 60 meters), while the effective diffusivity in Run 1 is 2.9×10^4 cm^2/sec for the same scale, and the agreement is good.

It may, therefore, be concluded that the values of diffusion characteristics estimated in the present study are consistent with those obtained in other diffusion studies of the Great Lakes.

Theoretical Models of Pollutant Diffusion from Continuous Sources

The distribution of a pollutant from a continuous source may be considered as the sum of the distribution of an infinite number of infinitesimal instantaneous sources discharged in a rapid sequence of time. Under this assumption, it is possible to superpose a solution for an instantaneous source with respect to time to obtain the distribution of concentration for the case of continuous discharge. Thus, in the case where there is a variable flow, $U(t)$, and where a pollutant is discharged at a variable rate, $Q(t)$, from a point source at (x_o, y_o), the concentration, $S_c(x,y,t)$, at (x,y) at t after initiation of discharge is given by

$$S_c(x,y,t) = \int_0^t \frac{Q(t')}{D} S_I\left(x-x_0-\int_{t-t'}^{t} U(t'')dt'', y-y_0, t'\right) dt' \quad , \qquad (11)$$

where S_I represents a concentration for instantaneous release from a point source of unit intensity; D is the depth of water within which the pollutant is assumed to be mixed uniformly. The depth, D, may be taken as the mean depth in nonstratified water and as the depth of the thermocline in stratified water.

Concentration from a finite-sized source can be obtained by integrating (11) with respect to x_0 and y_0 over the domain of source, A:

$$S_c(x,y,t) = \int_0^t dt' \iint_A dx_0 dy_0 \, \frac{q}{D} S_I\left(x-x_0-\int_{t-t'}^{t'} U dt'', y-y_0, t'\right) \quad ,(12)$$

where $q(x_0,y_0,t')$ is the rate of discharge of pollutant per unit area of the source.

The concentration distribution from a finite source becomes identical with the concentration from a point at sufficient distance from the source. If the distance is more than several times the size of the source, the finite source can be regarded, to a good approximation, as a point source with the same total rate of discharge.

We shall take Okubo and Pritchard's solution for S_I, since the solution has a mathematical form which can easily be integrated with respect to time; Joseph and Sendner's solution cannot be integrated over time to yield an analytical expression. Okubo and Pritchard's theory gives

$$S_I(x,y,t) = \frac{1}{\pi\omega^2 t^2} \exp\left\{-\frac{x^2+y^2}{\omega^2 t^2}\right\} \quad . \qquad (13)$$

Substitution of (13) into (11) provides the concentration distribution from a continuous point-source with a given release rate Q and field velocity U. Consider the special case of uniform flow and constant rate of discharge at $x_o = y_o = 0$. Equation (11) can then be easily integrated to give

$$S_c(x,y,t) = \frac{Q/D}{2\sqrt{\pi}\omega(x^2+y^2)^{1/2}} \exp\left\{-\frac{U^2y^2}{\omega^2(x^2+y^2)}\right\}\left[1-\Phi\left\{\frac{\sqrt{x^2+y^2}}{\omega}\left(\frac{1}{t}-\frac{xU}{x^2+y^2}\right)\right\}\right] \tag{14}$$

where $\Phi(\eta) \equiv \frac{2}{\sqrt{\pi}}\int_0^\eta e^{-a^2}\,da$: is equivalent to the error function.

The concentration along the central axis of a pollutant plume $(y = 0)$ takes the following simple form:

$$\begin{aligned} S_c(x,0,t) &= \frac{Q/D}{2\sqrt{\pi}\omega x}\left[1-\Phi\left\{\frac{U}{\omega}\left(\frac{x}{Ut}-1\right)\right\}\right] \quad \text{for } x \geqq 0 \\ &= \frac{Q/D}{2\sqrt{\pi}\omega|x|}\left[1+\Phi\left\{\frac{U}{\omega}\left(\frac{x}{Ut}-1\right)\right\}\right] \quad \text{for } x < 0 \ . \end{aligned} \tag{15}$$

Thus the concentration down the central line of plume varies inversely with x for $x \leqq x_\ell \left(1 - 2.326 \frac{\omega}{U}\right)$, where $x_\ell = Ut$ and decreases rapidly at large distances $(x > x_\ell)$. At the point x_ℓ (the location of the center of mass of the first patch released) the concentration is exactly one-half of what it would be if it decreased everywhere inversely with x. As time goes on, the inversely linear regime extends farther and farther from the source. The upstream concentration reduces quite rapidly with the distance from the source.

The situation where U is not constant, but a function of time, is identical with the foregoing except that the releases are not uniformly distributed along the center line of the plume, being more closely spaced when released near slack water than when released under swift current conditions. However, this more general case cannot be handled except by computer. Carter (17) used the Okubo and Pritchard solution to compute an exclusion area around a sewage outfall in a tidal estuary. He considered the constant current model to be adequate under conditions of variable Q and U, if some care or adjustment was made for the ratio ω/U.

Equation (14) may also be applied to a nonsteady case after a change of current takes place in a completely opposite direction. There we consider only a newly started plume. In fact, the old plume makes some contribution of contamination to the area of concern, but the amount should be negligible compared with that due to the new plume.

Close to the shore area the effect of boundary must be taken into consideration. Fortunately, the currents are predominantly longshore in the regime, so that the method of images may be applied to handle the proper boundary conditions (Carslaw and Jaeger, 16). Thus, where there is a constant current parallel to a straight shoreline and a point source is located at shore, the concentration distribution will be simply twice that derived from equation (14).

Prediction of Pollution Distribution

The foregoing solutions for a continuous release with a given rate of discharge contain only the physical parameters ω, the diffusion velocity, and U, the mean velocity. Since the drogue studies provided information on probable values of these parameters, we may now predict the concentration distribution of pollutant on the basis of the solutions.

First of all we must clarify our pollution problem. In southern Lake Michigan east of Chicago, the main sources of pollution are the Calumet River system discharging into Calumet Harbor and Indiana Harbor. The area of the drogue studies lay between these two sources. The closest water intake is located 4.0 km SE of Calumet Harbor and about 6.4 km NW of Indiana Harbor. Other water intakes are situated about 6.4, 9.6, 20.8, and 27.2 km north of Calumet Harbor. The shoreline of the area can be approximated by a straight boundary. The two sources of pollution may be regarded as point sources placed at the boundaries so far as the concentration distributions at these water intakes are concerned. Distances of these water intakes from the shore are 1 to 4 miles. A depth of 8 m is considered to be the mean depth of the area studied.

In western Lake Erie north of Cleveland, the main sources of pollution are the Rocky River and the Cuyahoga River. In addition, a 300-m diffuser of sewage effluent is proposed for the eastern end of Breakwater. Water intakes are located at about 4 miles NW of the mouth of Cuyahoga River. Approximate distances from these intakes either to the Rocky River or to the diffuser are 9.6 km. The shoreline of this area can also be assumed to be a straight boundary. The size of the pollutant sources, e.g., the width of the mouth of the Rocky River, may also be assumed to be small with respect to the distances to the water intakes. A depth of 12 meters is taken as the mean depth of the area.

In western Lake Erie south of the Detroit River, the main source of pollution is the Detroit River, which discharges 5,150 m^3/sec

(175,000 cfs) of water under average conditions (Hunt, 42). We will consider the distribution of pollutant in the shore regime of the State of Michigan, extending from Pointe Mouillee to La Plaisance Bay; this region may be assumed to be semi-bounded by a straight shoreline. A depth of 5 meters is taken as the mean depth of the area. The width of the lower Detroit River, being about 6.4 km, cannot be regarded as small as far as the studied area is concerned.

I) Predictions for Lake Michigan (east of Chicago) and Lake Erie (north of Cleveland).

We shall choose the solution (14), multiplying by 2 for the reflective boundary condition at y = 0, for our predictions. Let us transform the solution into a nondimensional form by taking b as a representative length-scale and the mean velocity, U, as a representative velocity. Designating $\omega_1 = \omega/U$, $x_1 = x/b$, $y_1 = y/b$, and $t_1 = t/(b/U)$, we express the solution as

$$C = \frac{1}{\omega_1\sqrt{x_1^2+y_1^2}} \exp\left\{-\frac{y_1^2}{\omega_1^2(x_1^2+y_1^2)}\right\}\left[1+\Phi\left\{\frac{\sqrt{x_1^2+y_1^2}}{\omega_1}\left(\frac{1}{t_1}-\frac{x_1}{x_1^2+y_1^2}\right)\right\}\right] \tag{16}$$

$$\text{where} \quad C = \frac{\sqrt{\pi}DbUS_c}{Q} \equiv \frac{S_c}{S_o} \tag{17}$$

$$\text{with} \quad S_o = \frac{Q}{\sqrt{\pi}DbU} \; . \tag{18}$$

The reference concentration, S_o, is what we would obtain if a pollutant released during a time interval T were mixed uniformly throughout a volume of water, $\sqrt{\pi}bDU/T$. Thus, if a river discharges a pollutant, S_r being its concentration, at a speed of U_r at the mouth of width b_r and depth D_r, the reference concentration is given by

$$S_r \frac{b_r D_r U_r}{\sqrt{\pi}bDU} \; .$$

A convenient unit of b is a mile for the two areas. Thus, appropriate ranges of x_1 and y_1 for prediction of concentration of contaminant will be $-5 \leqq x_1 \leqq 20$ and $0 \leqq y_1 \leqq 10$. Two values of ω_1 are selected from Table 8-2: $\omega_1 = 0.2$ and 0.4. These represent the two extreme situations. Figures 8-36 and 8-37 show the steady-state distributions of pollutant for the cases where $\omega_1 = 0.2$ and 0.4, respectively. Concentrations along the shore ($y_1 = 0$) and at $y_1 = 2$ and $y_1 = 4$ are shown in Figures 8-38 to 8-40 for the given values of ω_1. It may be noticed that, for the larger ω_1, more contamination spreads laterally, especially in the region of small values of x_1, and some contaminant is found in the upstream region.

For the nonsteady case we shall restrict the computation to the central line, $y_1 = 0$. Figures 8-41 and 8-42 show the distributions for various times with $\omega_1 = 0.2$ and 0.4, respectively, where the unit of time t* corresponds to the time it takes a pollutant particle to travel a distance $x_1 = 20$ with the speed U; thus, at the end of $t^* = 1$, the center of mass of the first patch released has just arrived at $x_1 = 20$, i.e., 20 miles from the source.

II) Predictions for Lake Erie (south of the Detroit River).

A steady-state case for a finite source in semifinite space has to be treated by numerical computation. The following result is due to H. H. Carter (unpublished notes).

Take a plane source of length b and depth D extending from the shoreline perpendicularly into the Lake. A nondimensional form of the solution is written as

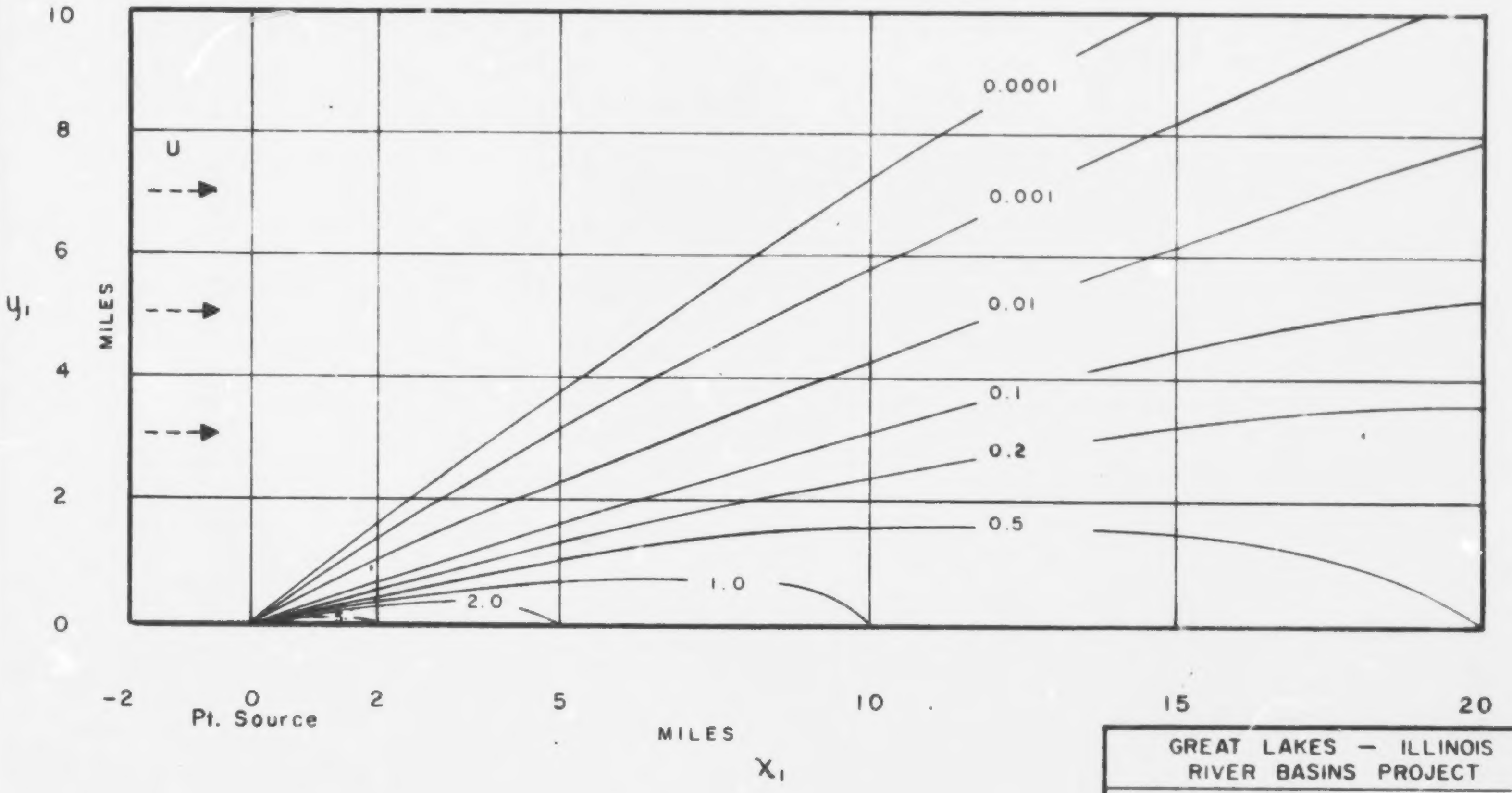
$$C = \frac{S_c}{S_o} = \frac{1}{2}\int_{-1}^{1} \frac{1}{\omega_1\left\{x_1^2+(y_1^2-y_o^2)\right\}^{1/2}} \exp\left\{-\frac{(y_1-y_o)^2}{\omega_1^2\left\{x_1^2+(y_1^2-y_o^2)\right\}}\right\} \times$$

$$\left[1 + \Phi\left\{\frac{x_1}{\omega_1(x_1^2+(y_1^2-y_o^2))^{1/2}}\right\}\right] dy_o \quad . \tag{19}$$

The right-hand side of (19) is handled by machine computation. Thus the relative concentration at a specific position depends only on the value of the parameter ω_1.

Figure 8-43 shows the result of computation of the relative concentration for the case $\omega_1 = 0.2$. In the region where $x_1 \leqq 5$, the

RELATIVE CONCENTRATION FROM A POINT SOURCE



1 MILE = 1.6 KILOMETERS

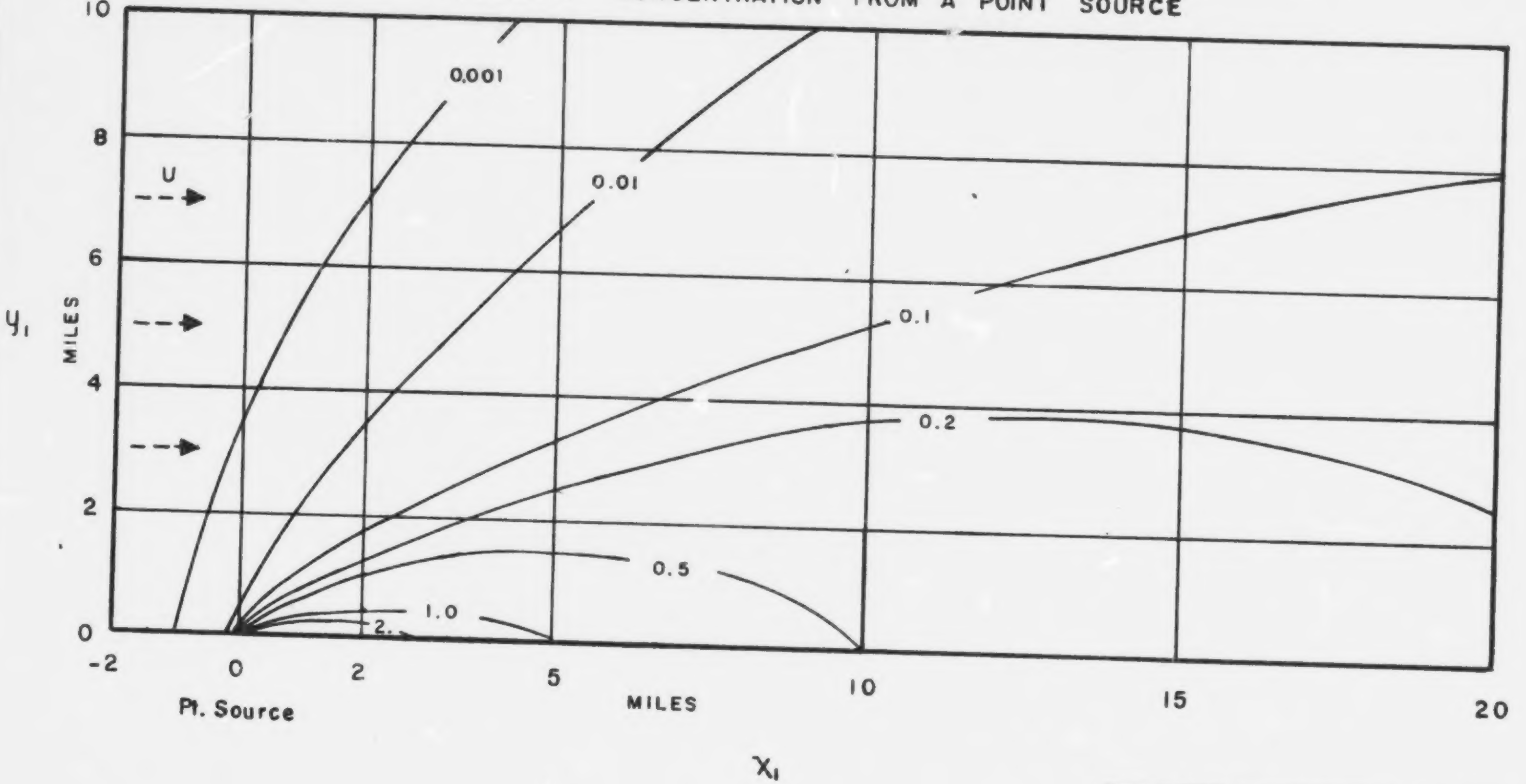
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STEADY-STATE DISTRIBUTION
$\omega_1 = 0.2$

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-36

RELATIVE CONCENTRATION FROM A POINT SOURCE



$\omega_1 = 0.4$

1 MILE = 1.6 KILOMETERS

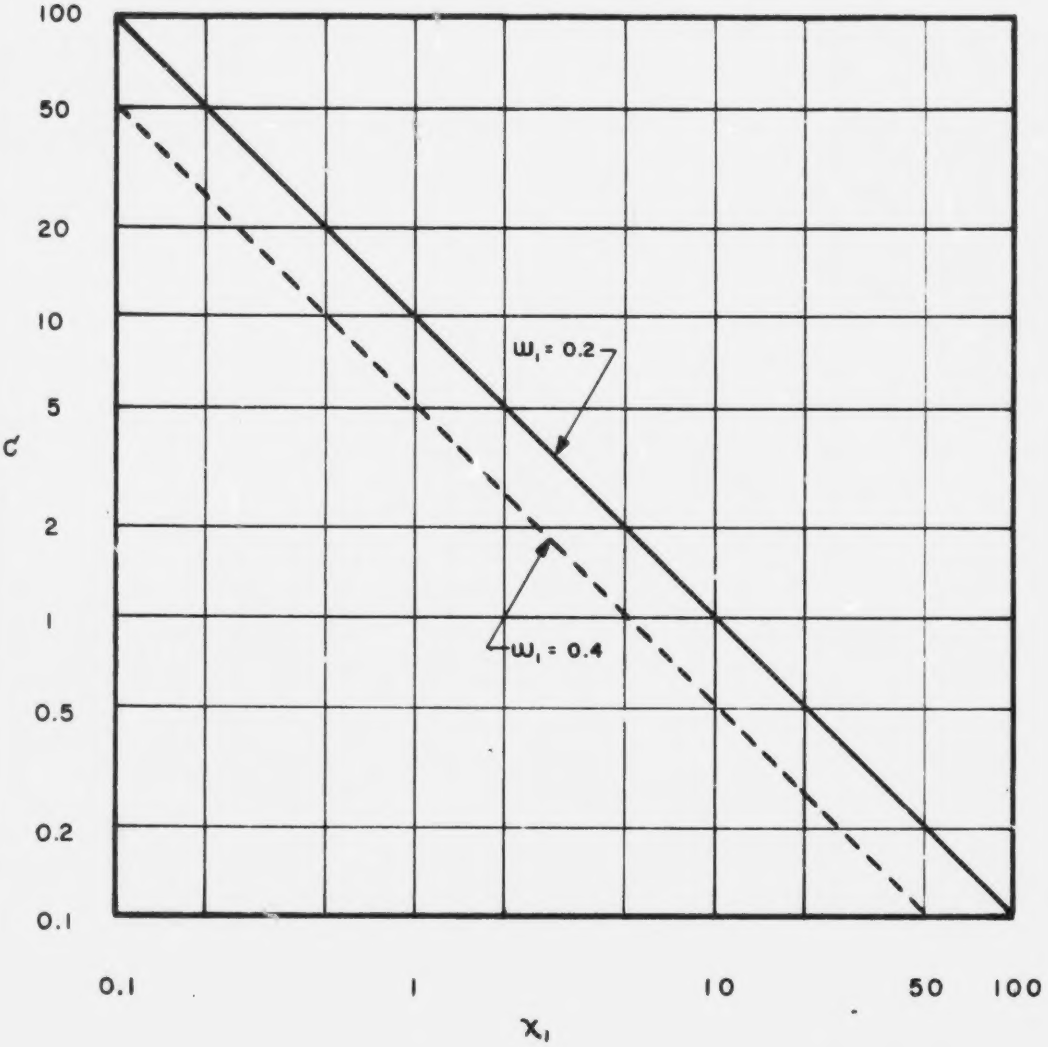
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

STEADY-STATE DISTRIBUTION
$\omega_1 = 0.4$

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-37

CONCENTRATION ALONG THE SHORELINE



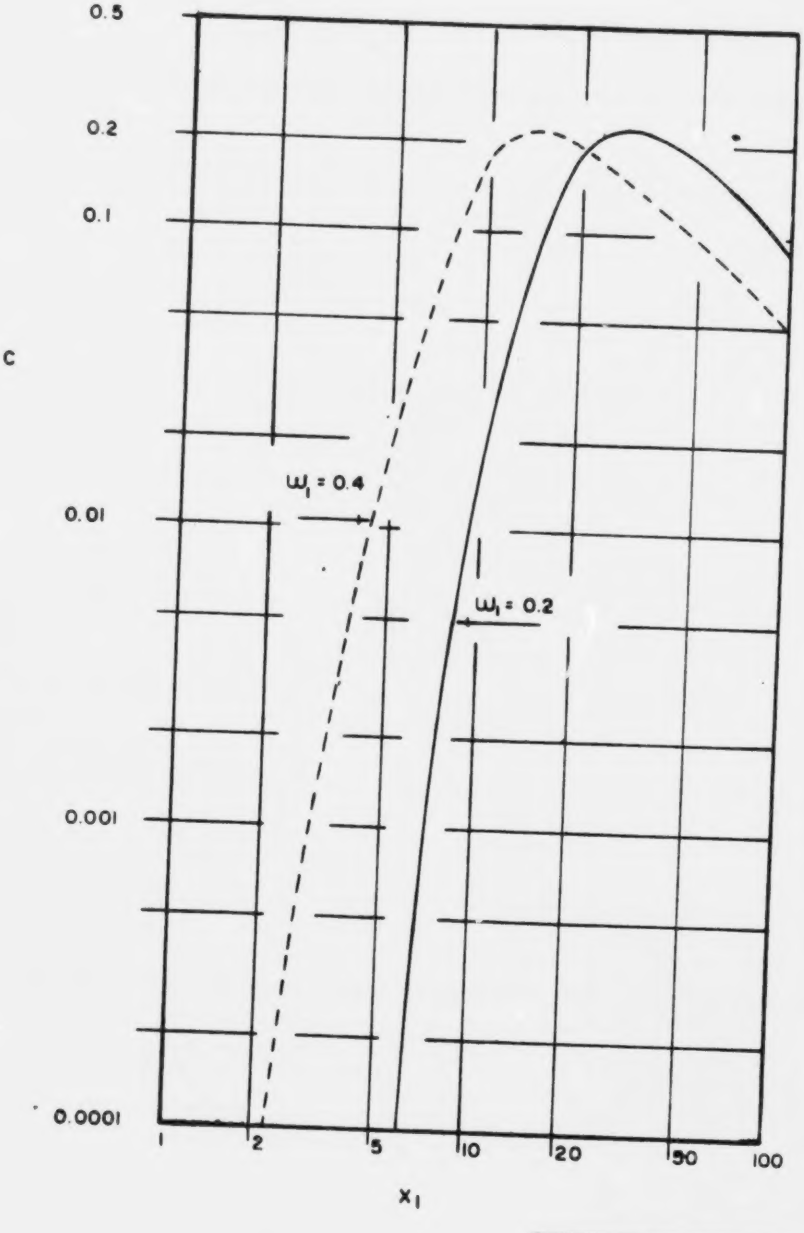
GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

RELATIVE CONCENTRATION

$y_1 = 0$

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 8-38

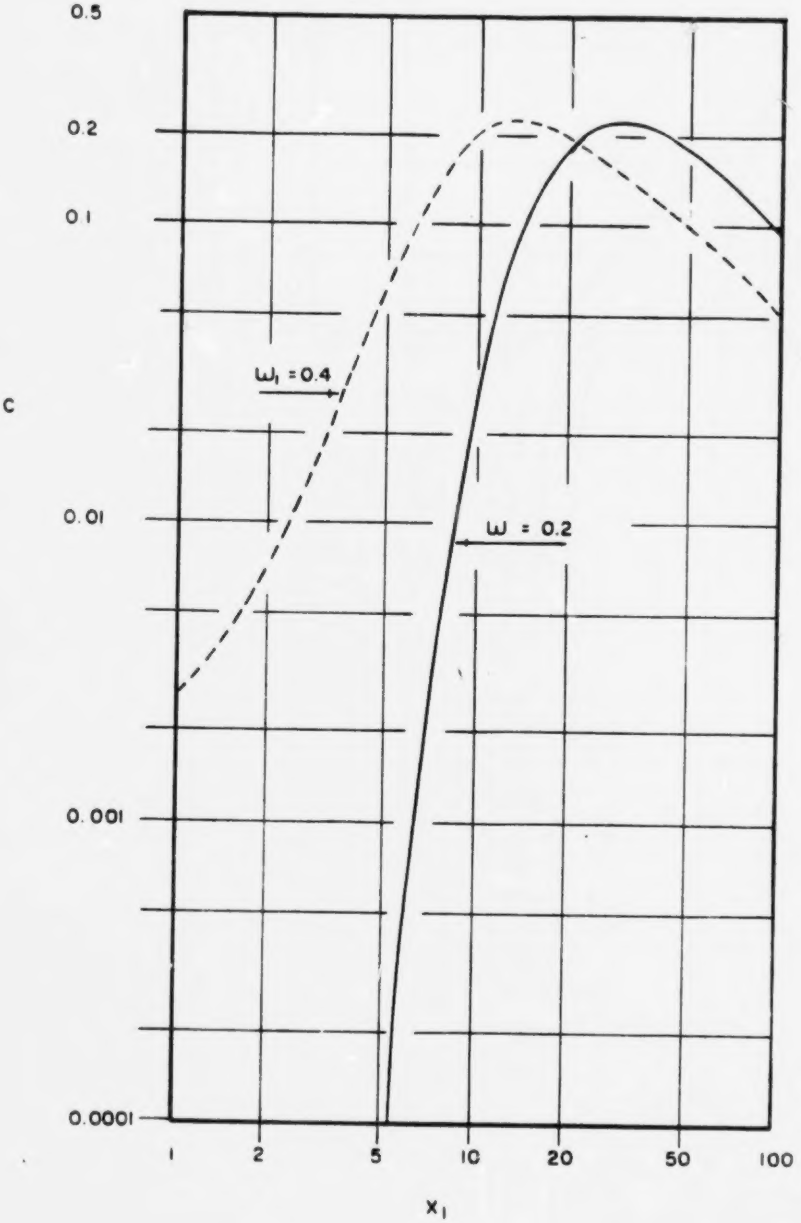


GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

RELATIVE CONCENTRATION
AT $y_1 = 2$

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-39

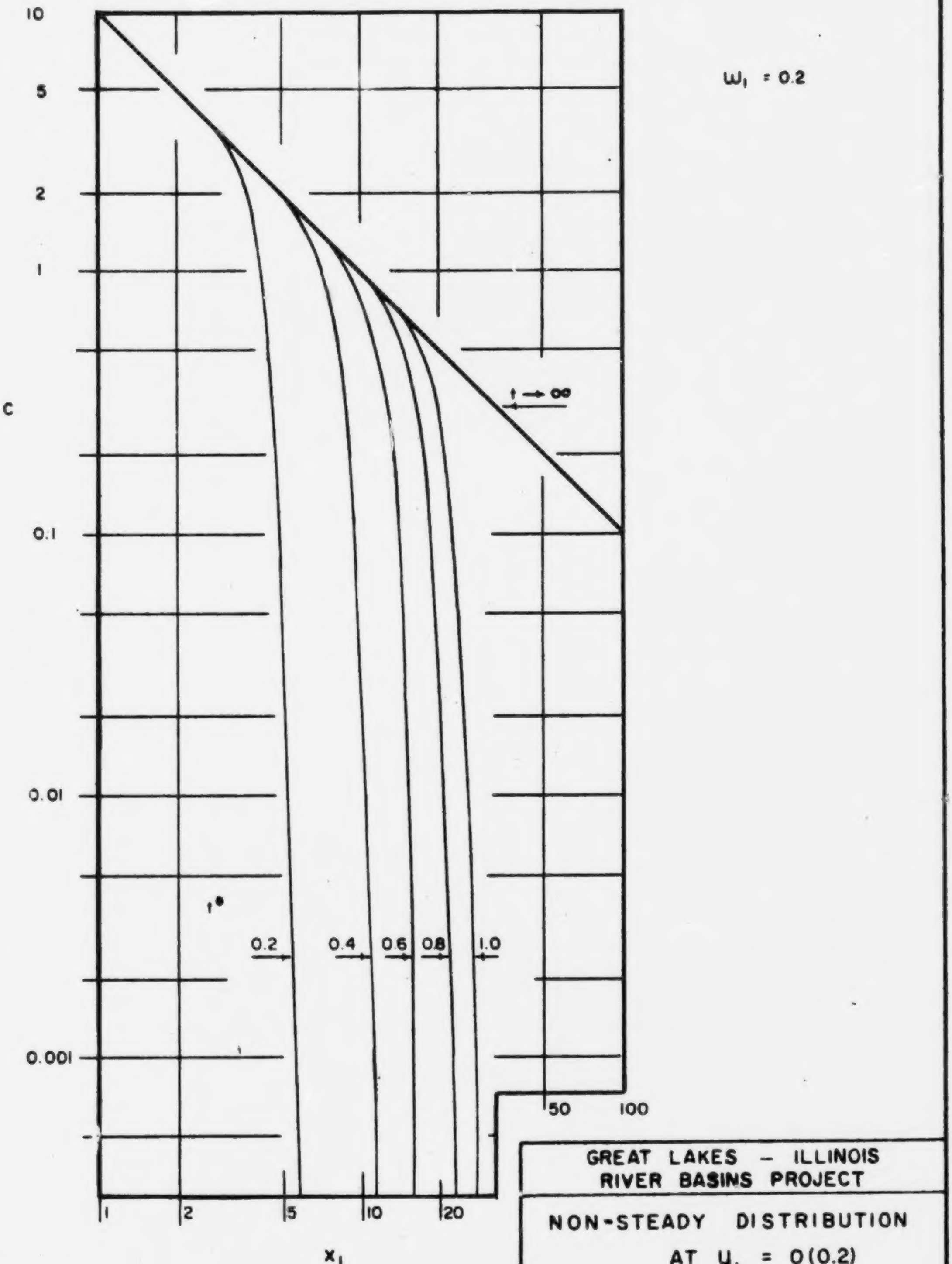


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

RELATIVE CONCENTRATION
AT y_1 = 4

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8 - 40



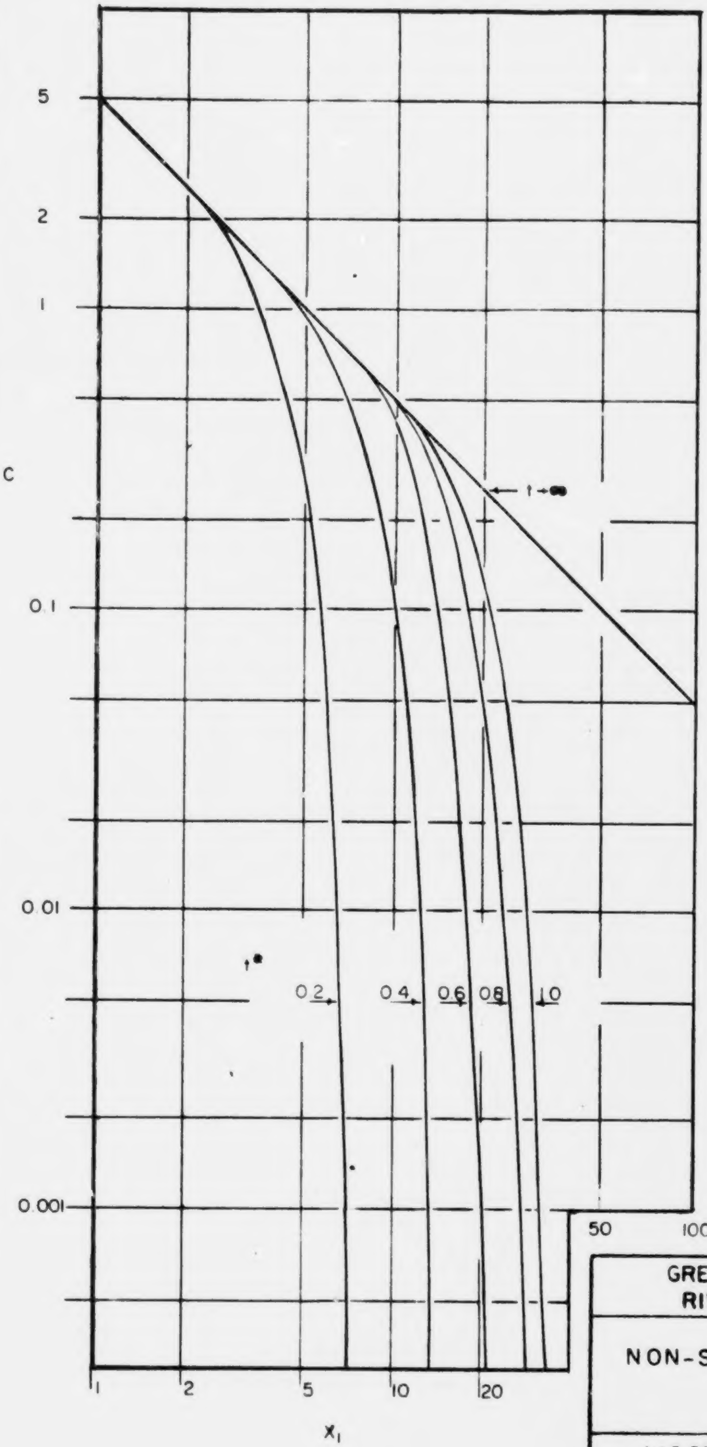
GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

NON-STEADY DISTRIBUTION
AT y_1 = 0(0.2)

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-41

$\omega = 0.4$

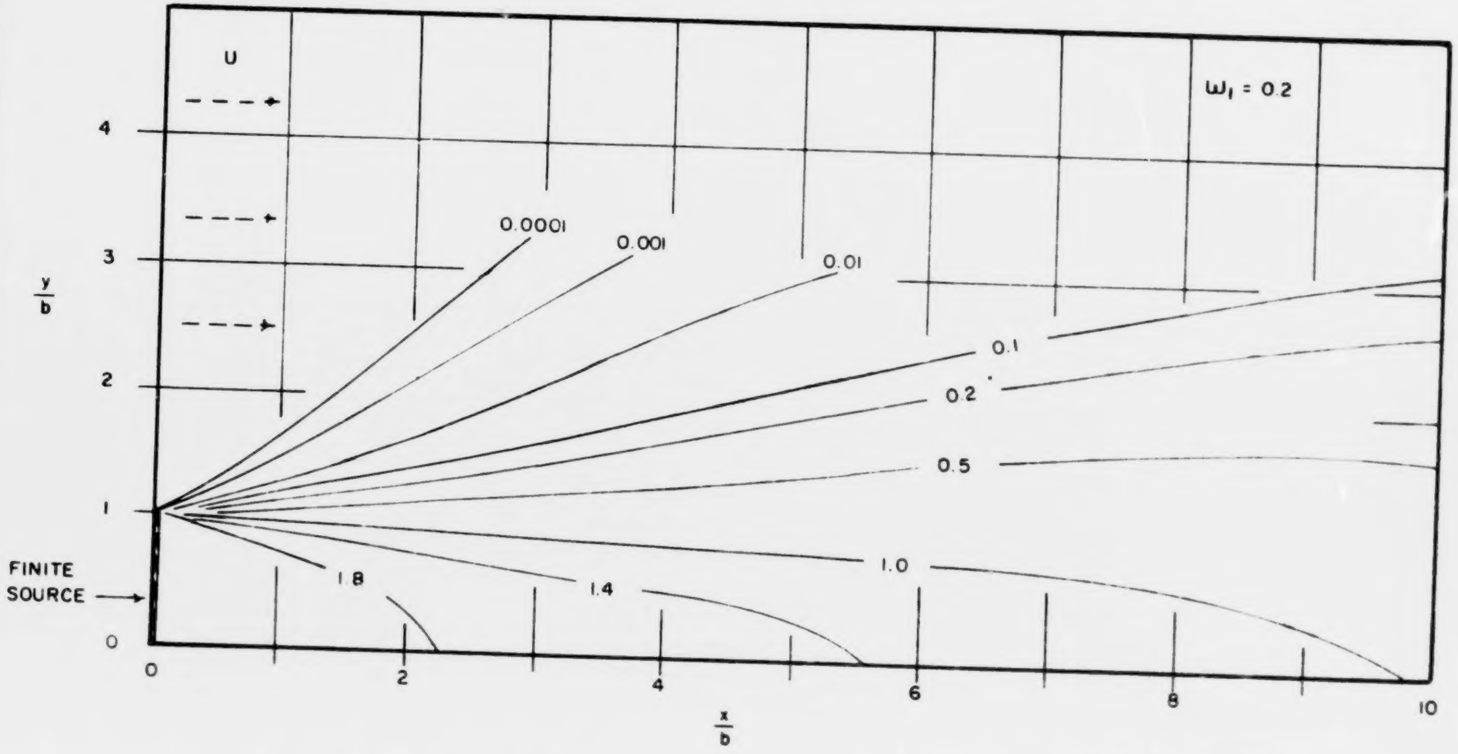


GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

NON-STEADY DISTRIBUTION
AT $y_1 = 0 \, (0.4)$

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-42



STEADY-STATE DISTIRBUTION OF RELATIVE CONCENTRATION
FROM A FINITE SOURCE

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

RELATIVE CONCENTRATION

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 8-43

relative concentration differs appreciably from that of a point-source solution, as may be expected.

Discussion

The main purpose of the drogue studies in Lake Michigan and Lake Erie was to provide basic information on the scale and intensity of horizontal diffusion. The use of marked drogues for studying turbulent diffusion, however, has limitations. One limitation is that the drogue has a finite size so that small-scale turbulence will not be sensed by the drogue. The drogue study will, however, obtain information on the medium-scale and larger turbulence.

Another limitation is that the drogue provides no information on the vertical component of turbulence. The effect of vertical diffusion, in particular when combined with vertical shear in the mean flow, on the mixing of a solute has recently received much attention by various investigators (Bowden, 13, etc.).

Csanady (22) reported that longitudinal (i.e., along mean current) diffusion of a dye patch in Lake Huron was considerably faster than lateral diffusion and the difference was attributed to the shear effect. In other words, horizontal diffusion is greatly accelerated, compared with diffusion in uniform flow, in complex currents. Thus effective longitudinal-diffusivities due to the shear effect may be comparable with apparent diffusivities found by purely two-dimensional experiments, e.g., drogue studies. This may suggest that our estimate of the horizontal diffusion obtained from our drogue studies should be regarded as a lower limit for mixing in a lake. In other words, the drogue study provides upper limits of steady-state concentrations resulting from the distribution of a pollutant.

Summary

The results of the drogue studies in Lake Michigan and Lake Erie are summarized as follows:

1. More than half of the groups of drogues showed a regular pattern of turbulent dispersion, whereas a few groups exhibited a suppression or reversal of diffusion caused primarily by convergences.

2. The movement of the 1.5-m drogues was generally in the direction of local winds. On the other hand, the 6.1-m drogues moved against the winds. The existence of vertical shear is obvious. Typical velocities are 4 and 2 cm/sec at 1.5 and 6.1 m, respectively.

3. An effective diffusivity ranges from 2.9×10^4 to 5.5×10^4 cm^2/sec.

4. The intensity of turbulence differs little between the two Lakes. A typical value for the intensity of turbulence is 0.3 to 0.4 cm/sec.

5. In Lake Erie the rate of energy dissipation at 6.1 m is less by an order of magnitude than that at 1.5 m. A similar order of magnitude exists between the two Lakes at 1.5-m depth, a typical value being 2×10^{-4} cm^2/sec^3.

6. The length-scale of the energy-containing eddies is estimated to be several meters.

7. Diffusion velocities according to the theories of Joseph-Sendner and Okubo-Pritchard are also computed. The result shows that the turbulent diffusion in the surface layer seems to be more intense in Lake Erie than in Lake Michigan.

8. Generally speaking, the values of diffusion characteristics obtained in the drogue studies are consistent with those obtained by other methods, e.g., dye studies.

9. Some predictions of concentration of a pollutant which is discharged continuously are given on the basis of superposition of a solution for an instantaneous point-source.

CHAPTER 9

METEOROLOGICAL STUDIES

Introduction

Meteorological studies were conducted on Lake Michigan in conjunction with the work described in other parts of this report, for the purpose of gaining knowledge about the relationship of lake currents to weather. The conception, planning, and conduct of these studies were achieved through a cooperative arrangement between GLIRB Project and the U.S. Weather Bureau -- now a part of Environmental Science Services Administration (ESSA).

ESSA provided a resident meteorologist on full-time staff duty with the Project. From the inception of the study through November, 1964, this position was filled by Mr. George Williams (now deceased); his place was taken by Mr. J. B. Holleyman. Technical guidance on the part of ESSA came from Dr. D. L. Harris.

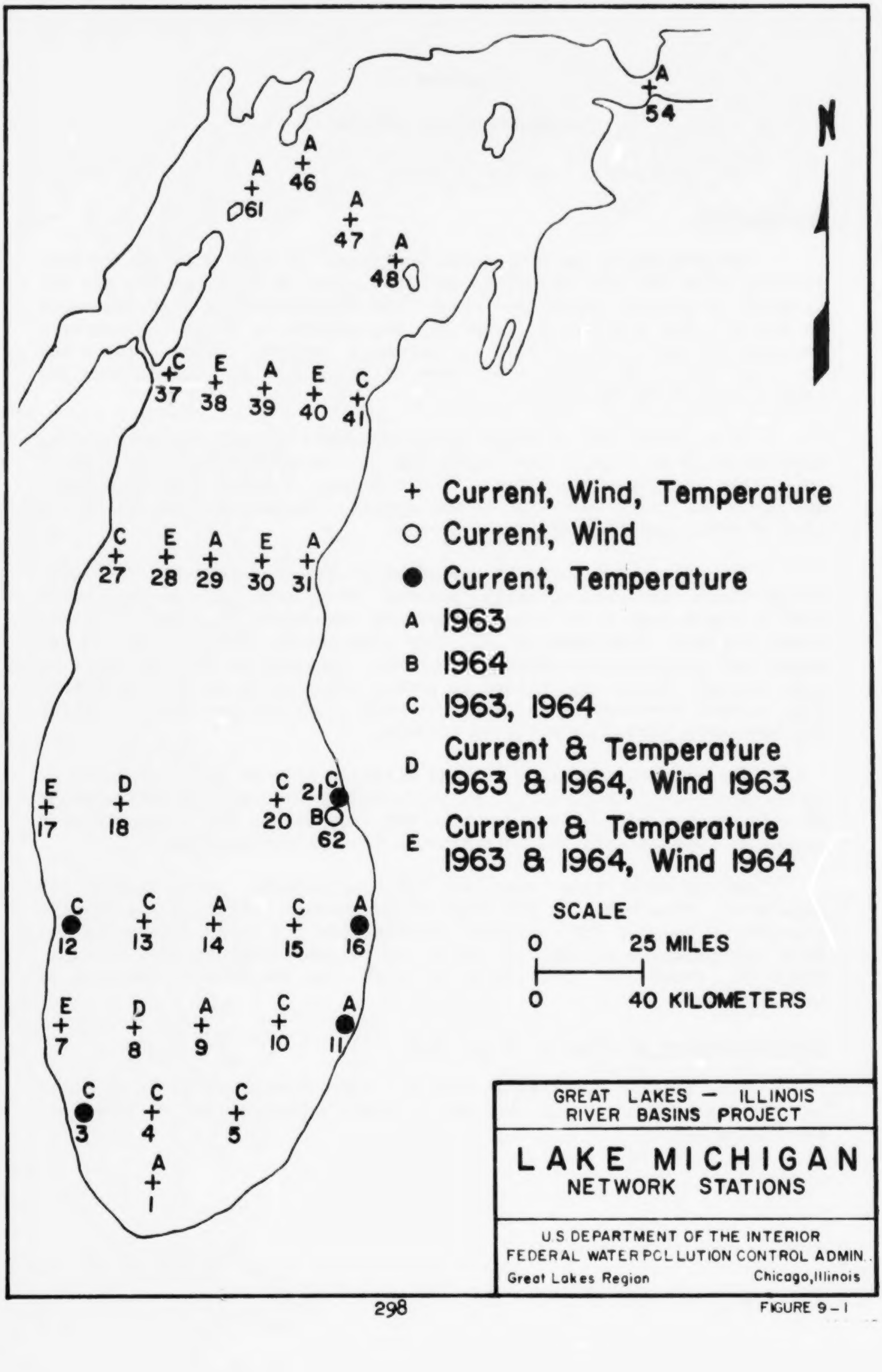
The original intent of meteorological studies was to learn enough about the relationship between winds over the Lake and winds over adjacent land to be able to forecast lake winds from land observations, perhaps supplemented by data from ships. In addition, it was hoped that sufficient knowledge about the response of lake currents to wind regimes would be gained to permit translation of wind forecasts into current forecasts. As will be seen, this far-reaching objective has been only partially achieved to date.

The network installed in Lake Michigan late in 1962 consisted of 33 current meter stations with subsurface temperature recorders attached. Twenty-two of the stations also had instruments for recording wind velocity. The network was in operation during 1963 and 1964.

During this time some of the instruments were damaged or destroyed, thus reducing the size of the network. Figure 9-1 gives the location of each of the network stations and the type of instrumentation in operation as well as the period of operation of each station. Table 9-1 shows the wind data available from the network stations on Lake Michigan.

Instrumentation and Collection of Data

The network stations in Lake Michigan were oriented in an east-west line across the Lake and were spaced approximately 32 km apart, see Figure 9-1.


A 54
A 46
A 61
A 47
A 48
C 37
E 38
A 39
E 40
C 41
C 27
E 28
A 29
E 30
A 31
E 17
D 18
C 20
C 21
B 62
C 12
C 13
A 14
C 15
A 16
E 7
D 8
A 9
C 10
A 11
C 3
C 4
C 5
A 1
N
+ Current, Wind, Temperature
○ Current, Wind
● Current, Temperature
A 1963
B 1964
C 1963, 1964
D Current & Temperature 1963 & 1964, Wind 1963
E Current & Temperature 1963 & 1964, Wind 1964
SCALE
0 25 MILES
0 40 KILOMETERS

GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

LAKE MICHIGAN NETWORK STATIONS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 9 – 1

TABLE 9-1

LAKE MICHIGAN WIND DATA

STATION	DEPTH-HEIGHT METERS	LATITUDE	LONGITUDE	FILM NO. 200-	DATE IN	TIME CST	DATE OUT	TIME CST
01	003	41°48.0'	87°21.0'	038	07/24/63	1350	09/04/63	0900*
04	003	42°01.0'	87°20.0'	334	06/22/64	1740	07/06/64	1640
05	003	41°59.0'	87°00.0'	037	08/08/63	1145	08/26/63	1000*
05	003	41°59.0'	87°00.0'	333	05/12/64	1043	07/06/64	0855
07	003	42°45.0'	87°45.0'	346	04/10/64	1410	06/16/64	1300
08	003	42°23.0'	87°25.0'	066	07/30/63	1750	10/16/63	1100
09	003	42°23.0'	86°59.0'	067	08/18/63	1330	10/17/63	1035
10	003	42°23.0'	86°38.0'	070	08/16/63	1045	10/17/63	0805
13	003	42°45.0'	87°22.0'	069	07/31/63	1330	10/18/63	1900
15	003	42°44.0'	86°35.0'	068	08/05/63	1900	10/17/63	1400
15	003	42°44.0'	86°35.0'	337	05/11/64	1005	07/05/64	1105
17	003	43°08.0'	87°51.0'	338	04/09/64	0830	07/09/64	1225
18	003	43°08.0'	87°24.5'	170	07/16/63	1500	11/10/63	1115
20	003	43°08.0'	86°35.0'	141	08/04/63	1330	11/07/63	1245
20	003	43°08.0'	86°35.0'	339	05/10/64	1025	07/05/64	0745
27	003	44°03.0'	87°33.0'	340	04/23/64	1020	07/10/64	0700
28	003	44°04.5'	87°14.5'	341	04/23/64	1400	07/10/64	0757
30	003	44°04.0'	86°48.0'	342	04/19/64	0725	07/04/64	0925
37	003	44°50.0'	87°09.0'	106	10/06/63	2035	10/29/63	1005
40	003	44°43.0'	86°31.0'	345	04/19/64	1515	07/03/64	1530
41	003	44°39.0'	86°20.0'	169	08/22/63	1000	11/05/63	1325
47	003	45°22.0'	86°14.0'	095	10/04/63	1430	10/31/63	1645
48	003	45°12.0'	86°02.0'	086	10/04/63	1120	10/25/63	0305
54	003	45°48.5'	84°44.5'	081	09/24/63	1510	10/30/63	1935
61	003	45°47.0'	86°47.0'	076	09/23/63	1310	10/29/63	1625
62	003	Muskegon Tower Buoy		371	07/22/64	1155	09/24/64	1800

*Estimated

TABLE 9-1 (Continued)

LAKE MICHIGAN WIND DATA

STATION	COMPUTED TIME INTERVAL BETWEEN RECORDS	SPEED SCATTER EST. OF 1%	% VANE READINGS DIFFER BY 30°	45°	REMARKS
01	20.02	07.0	----	----	Station broke loose, recovered data.
04	19.90	00.0	00.4	----	Estimated time recovered.
05	-----	03.0	----	----	Speeds too high, recomputed.
05	20.00	05.0	02.9	----	Record valid only to 6/16/64, 1300.
07	19.16	50.0	----	----	
08	20.01	00.0	03.5	----	
09	20.01	04.0	02.9	----	
10	20.02	03.0	01.9	----	
13	19.99	05.0	02.6	----	
15	19.98	----	02.5	----	
15	-----	00.0	01.3	----	Short record, light struck unknown period.
17	20.00	07.0	00.1	----	
18	20.02	00.0	06.0	03.0	
20	20.02	00.0	00.3	----	
20	20.00	02.0	01.6	----	
27	20.03	05.0	01.7	----	
28	20.03	25.0	02.3	----	Speeds too high.
30	20.00	43.0	03.7	----	Speeds too high.
37	20.01	02.0	02.6	----	
40	20.00	20.0	02.6	----	Speeds too high.
41	20.01	02.0	01.4	----	
47	20.02	04.0	01.5	----	
48	20.79	01.0	02.4	----	Short record - recalculated.
54	20.00	04.0	02.1	----	
61	20.00	10.0	01.9	----	Speeds high.
62	20.00	----	----	----	

---- Unknown or not computed.

The network station is a floating buoy which is moored and untended. The wind instrument consists of a wind vane and three-cup anemometer which are mounted approximately 3.0 m above the water surface. Subsurface current instrumentation is described in other sections of this report.

The three-cup anemometer which measures wind speed and the wind vane which measures the wind direction were developed at Woods Hole Oceanographic Institution.

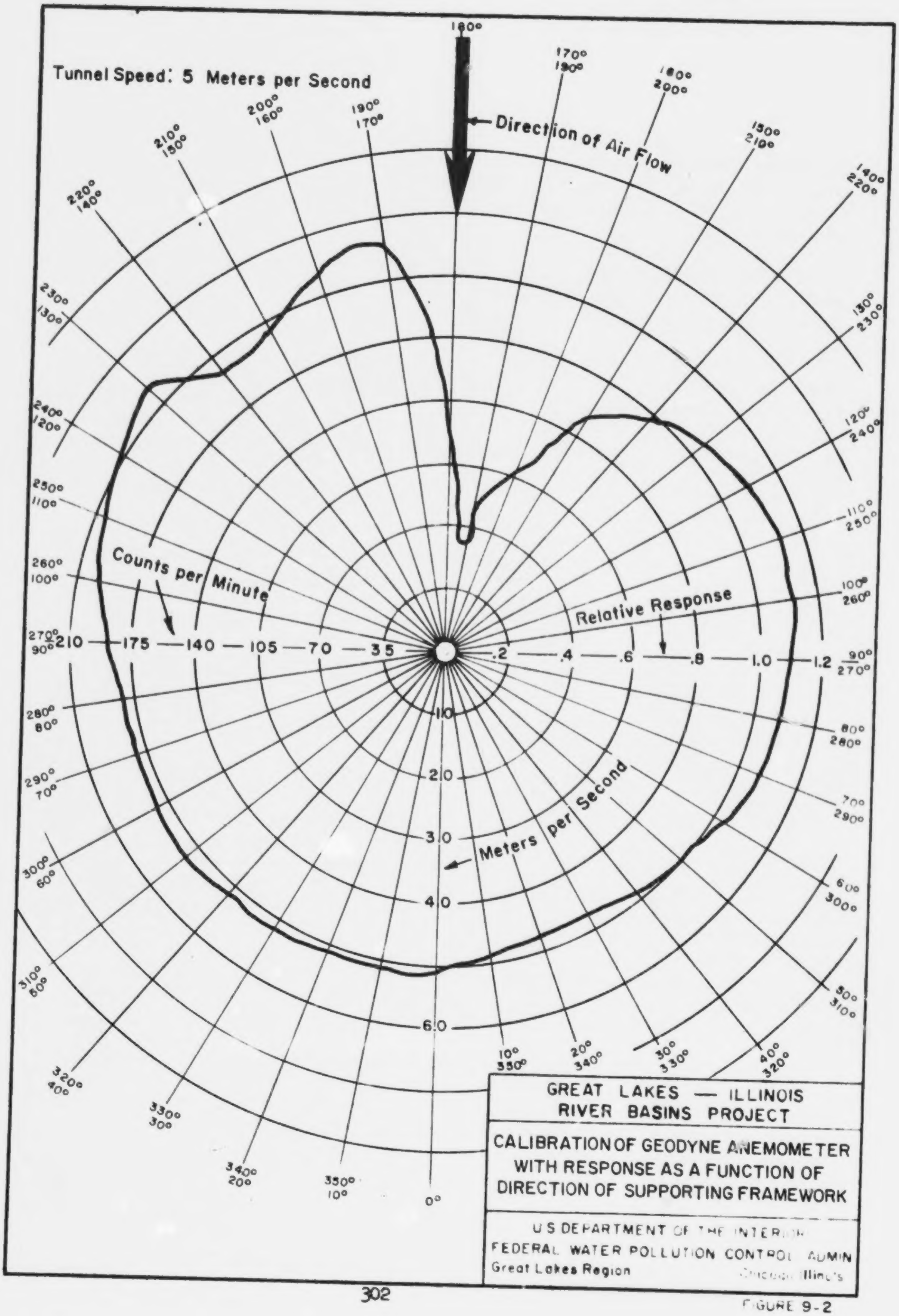
Wind observations as well as current observations are recorded digitally on 16 mm film in the form described by Webster (91). Each recorded direction gives the orientation of a given instrument to magnetic north and the wind direction relative to the instrument. Thus, it is possible to determine the true wind direction in spite of the changing orientation of the buoy system. For the anemometer each revolution and tenth revolution of the cups were recorded for a 6-second period in each 20-minute interval.

The anemometer sensitivity varies with the direction of the wind relative to the supporting framework. The direction calibration of two of the anemometers used, as determined in the University of Michigan Department of Meteorology and Oceanography wind tunnel, is shown in Figure 9-2. The essential features of this calibration agree with that determined at MIT and supplied to GLIRB Project before the calibration at the University of Michigan was completed. These instruments, however, were more sensitive than the manufacturer's specifications stated. That tested at MIT was less sensitive than the specifications.

A field comparison of all of the anemometers, carried out at Cleveland during the winter of 1964-65, showed that the response of all instruments after a year or two of field use agreed with that of the instruments calibrated at the University of Michigan, within an error of less than 5 percent, when the wind came from a direction nearly opposite to the vertical support. This was true even of instruments in which the cup shaft had been bent, presumably as the result of wave damage.

Directional calibration is readily reproducible to within 5 percent. Thus, corrections may be applied if the wind direction relative to the buoy is known with sufficient accuracy.

The magnitude of the calibration problem was not fully recognized until the summer of 1964 and the angle between anemometer and buoy framework needed to correct the earlier data, was not recorded. In the summer of 1964 a vane was added to the buoy stations, to keep the anemometer oriented in a favorable direction most of the time (Figure 9-3).

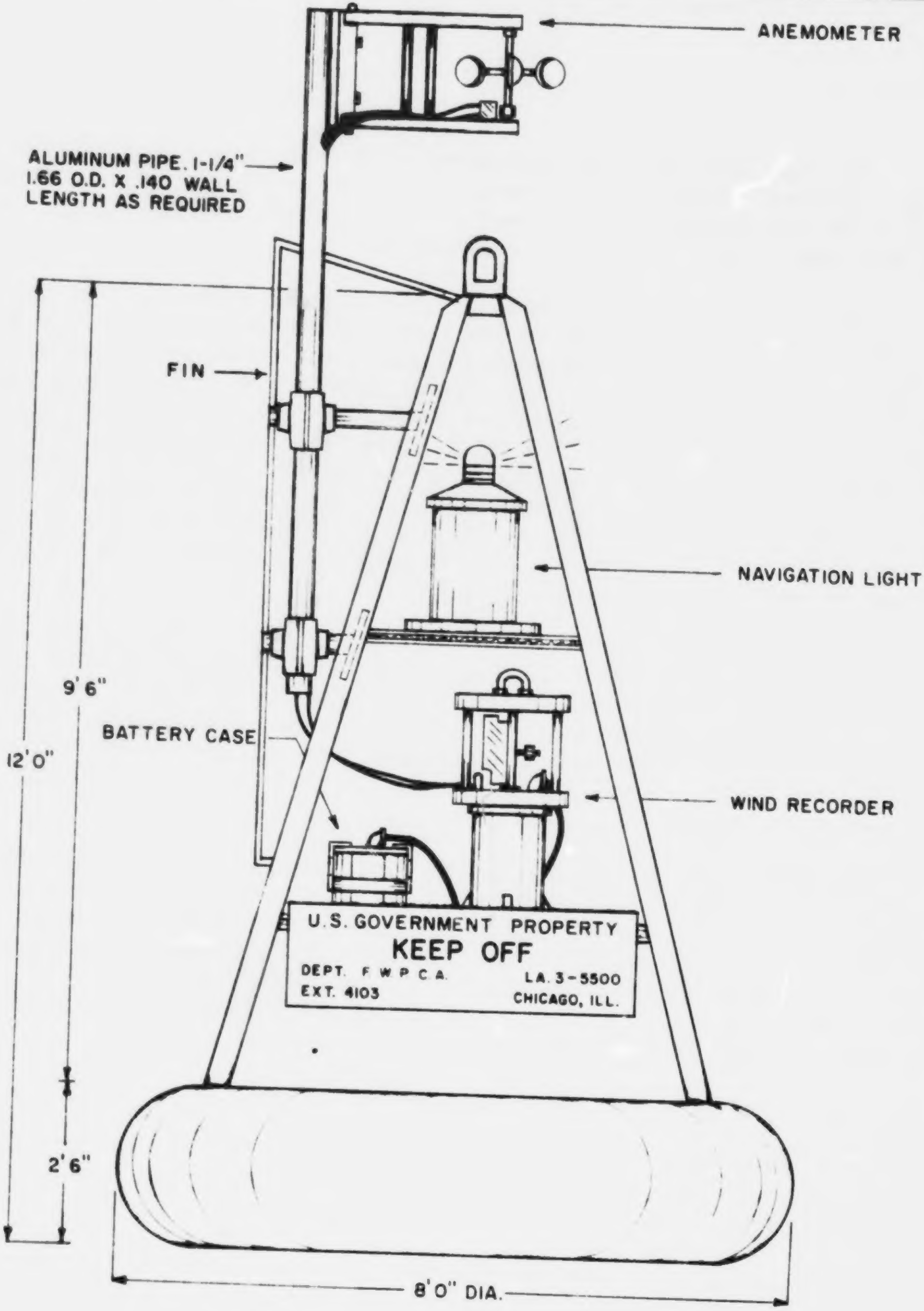


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

CALIBRATION OF GEODYNE ANEMOMETER
WITH RESPONSE AS A FUNCTION OF
DIRECTION OF SUPPORTING FRAMEWORK

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 9-2


ANEMOMETER
ALUMINUM PIPE. 1-1/4"
1.66 O.D. X .140 WALL
LENGTH AS REQUIRED
FIN
NAVIGATION LIGHT
9'6"
BATTERY CASE
12'0"
WIND RECORDER
U.S. GOVERNMENT PROPERTY
KEEP OFF
DEPT. F.W.P.C.A.
LA. 3-5500
EXT. 4103
CHICAGO, ILL.
2'6"
8'0" DIA.

1 INCH = 2.54 CENTIMETERS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

INSTRUMENT BUOY
TOROIDAL SHAPE
NOT TO SCALE

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region
Chicago, Illinois

FIGURE 9-3

The wind vane is more responsive than necessary for this type of study. However, much of the overshooting of the vane proper is eliminated by an oil-damped vane follower. The dynamic response of the full wind vane system has not been investigated.

The wind speed is recorded on photographic film as a series of light pulses spaced according to the speed of the anemometer. The wind direction is recorded as vane and compass position in Gray Binary code transmitted to the camera by fiber optic light pipes. The photographic film was developed and transferred from the film to a low density IBM compatible magnetic tape in binary format. The data from the magnetic tape were programmed by computer in three forms: 6-hour averages of wind directions and speeds, 2-hour envelopes, and histograms. The averages for each 6 hours (0, 6, 12, and 18 hours) were tabulated to include the number of observations, direction and speed, and the coefficient of variation of speed, Figure 9-4.

Two directional readings were obtained for each observational interval and the arithmetic mean of these two was accepted as the true direction. This process was adopted to reduce the effect of vane overshoot. A detailed examination of data samples from several stations indicated that the error due to overshoot was insignificant about 90 percent of the time and that this simple correction was sufficient for most overshoot errors.

Average winds were used rather than instantaneous winds because it is believed that average winds are more representative of actual conditions over a period of time. The average values considered were for periods to conform to the synoptic interval on weather charts. These values were obtained by converting velocity vectors into components along the x and y axes, averaging each component separately, and computing the vector resultant of these average components.

Two-hour envelopes as a rule smooth out enough of the small-scale features to make the dominant features of the wind field discernible. The 2-hour envelopes are obtained by plotting the maximum and minimum values of wind speed and accompanying direction for each 2-hour period being considered, Figure 9-5.

The histograms are two-dimensional distributions of wind speed versus wind direction for the total number of observations for an entire month, Table 9-4. From these values prevailing direction expressed in terms of net flow can be calculated by taking the algebraic sum of the products of wind speed and number of periods it occurs and that of a wind blowing in the opposite direction.

```
SIX HOURLY AVERAGES-STA.   5 - DEPTH   0 - TIME INTERVAL 20 MIN.

LAKE MICHIGAN                     0                  6                 12                 18

 MTH   DAY    YR      N   D  AN  SP      N   D  AN  SP      N   D  AN  SP      N   D  AN  SP
   8    10    63     18  27   4  17     18  23  13  11     18  55  25   9     18  18   3  11
                     17  12  14   9     18  19  22  12     18  89  32  10     18  37  33   5
   8    12    63     18  28  21   7     18  17  19  15     18  29  16  14     18  16  20  20
                     18  29  23  24     18  18  31  32     16  24  33  39     18  16  36  41
   8    14    63     18  13   1  32     18  27  36  23     18  17   0  21     17  38   3  14
                     17  45  25  10     18  15  25  17     18  45  25   9     18  25  13   8
   8    16    63     17  75  18  16     18  25  22  15     18  18  20  20     18  25  19  25
                     18  27  21  35     18  21  36  30     18  20  36  25     18  29   1  23
   8    18    63     18  25   5  20     18  30  14  13     17  35   6  10     18  25   5  13
                     18  19  12  12     18  23  16  12     18  28  10   6     18  16   5   6
   8    20    63     18  30  21  10     18  17  23  13     18  26  17   7     18  13  11   8
                     17  24  22  12     18  15  22  13     18  20  19   7     18  20  18   7
   8    22    63     18  14  22   1     18  16  24   8     18  71  15   8     18  42  13   7
                     18  18  20  10     18  18  21  12     17  23  20  10     18  18  18   8
   8    24    63     18  42  11  13     18  21   6  19     18  40   4  18     18  31   5  15
                     18  41   9  30     18  60  10  20     18   9   4  15     18  30   2  24
   8    26    63     17  -1   8   0     18  14  12  11     18  34   4  11     18  23   3  15
                     18  28   9  11     18  46  16   7     18  23  11  10     18  30  17  24
   8    28    63     18  -1  17   0     14  39  22  11     17  58  34   9     18  33  34   7
                     18  59  32  10     15  75  12   7     18  45  34   9     18  32  28   7
   8    30    63     18  45  29  10     17  57   5   9     11  70  18   7     17  58  32   7
                     17  32  30   7     15  63  13  10     17  99  13  11     18  36  25   7
   9     1    63     17  26  29   8     18  41  10  10     12  60  12   8     18  24  21   6
                     18  29  20   8     18  36  20  14     17  40  22  13     18  35  22   7
   9     3    63     18  39  29   9     18  39  10   6     18  45  19   6     18  63  13   5
                     17  83  21  10     15  80  21   8     10  82  11   8     17  45  11   7
   9     5    63     17  51  12   6     17  60   9  10     18  83   3   5     12  67   9  11
                     18  57  20   8     16  23  12   6     18  36  19   8     18  22  21  10
   9     7    63     18  41  24   9     18  34   2   7     17  99   5  10     18  66   4   6
                     14  69   0   6     13  99   4   8     13  70   6  11     18  83  15   7
```

STATION – 5

DEPTH 0 – WIND 3m. Ht.

LEGEND:

N -No. of Data Points
D -Coefficient of Variation
AN-Angle Average
SP-Speed Average

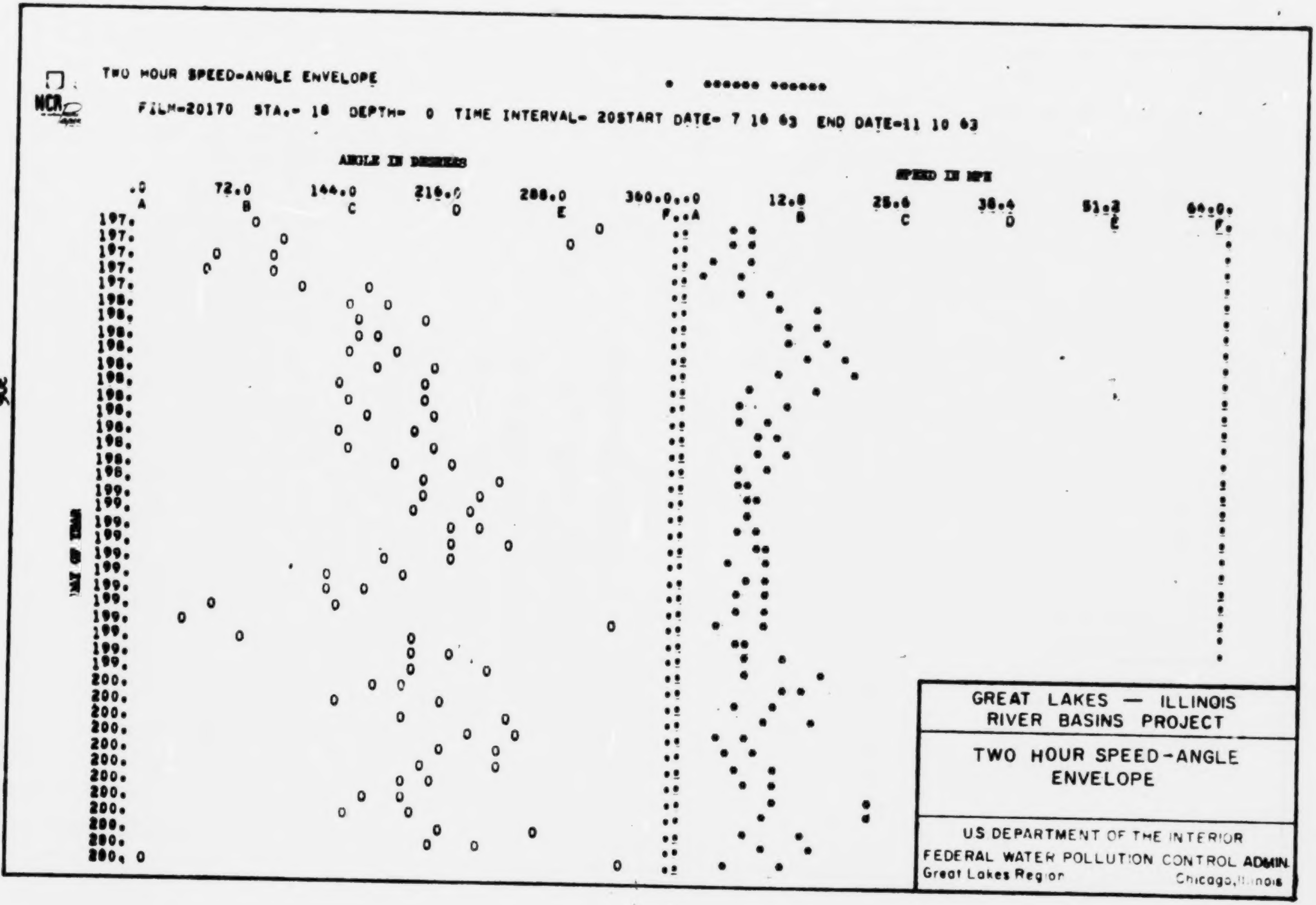
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

COMPUTER FORMAT OF

SIX-HOUR AVERAGES

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 9-4



TWO HOUR SPEED-ANGLE ENVELOPE

FILM-20170 STA.- 18 DEPTH- 0 TIME INTERVAL- 20START DATE- 7 10 63 END DATE-11 10 63

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TWO HOUR SPEED-ANGLE
ENVELOPE

US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 9-5

Climatology of Surface Pressures and Winds

The day-to-day winds, when combined into averages, give the climatology of the wind field over Lake Michigan and the other Great Lakes. The winds, instantaneous and averages, respond to the overall pressure field of the area. At this point it is well to discuss the climatology of the pressure and wind field in the Lake Michigan and Great Lakes area before presenting the results of the wind study.

Lake Michigan and the Great Lakes in general lie in the path of several of the major storm tracks that cross the United States. The low pressure areas that follow these tracks are more frequent in the winter than the summer, but traverse the Great Lakes area at all times of the year.

As a rule, low pressure areas that cross Lake Michigan follow two main paths. Those that develop in Colorado and the northern Rocky Mountains move northeastward or eastward across southern Lake Michigan. They are the winter-time lows. Those that form in the Canadian province of Alberta move southeastward across the northern United States and recurve eastward in the Great Lakes area. Lows that follow this track frequently cross Northern Lake Michigan and occur in the summer as well as the winter.

The Great Lakes not only lie in the path of some of the major storm tracks that cross the United States but also contribute to the intensification of low pressure areas that cross the region. At times lows intensify rapidly as they enter the western Great Lakes area of Lake Superior and Lake Michigan. Intensification occurs during the fall and winter when the water in the Great Lakes is warm in comparison with the very cold arctic or polar air that may follow immediately behind the center of the low. The intensification of the low may be so great that a major storm results.

Because of the great contrast in the fall and winter between the warm water of the Great Lakes and the cold arctic or polar air that crosses the bodies of warm water, low pressure areas may develop occasionally in the Great Lakes area. The probability of actual development is not great unless upper air conditions are right for the formation of the surface low. At any rate most of the lows that cross the Great Lakes develop farther to the west rather than over the Lakes themselves.

The prevailing winds over the Lake Michigan area reflect the average pressure field. The storm tracks that cross the Lake influence the average pressure field in such a way that the prevailing winds are from the southwest through west.

Data Analysis and Discussion

In analyzing the Lake Michigan wind data, the following procedure was followed:

1. Buoy winds were plotted on the printout charts of Lake Michigan.

2. Ship observations including ship winds for the standard 6-hourly synoptic times (00C, 06C, 12C, and 18C) were plotted.

3. The observations for surrounding land stations for the standard 6-hourly synoptic times were plotted on the same charts.

4. A pressure and frontal analysis was made on the chart so that geostrophic winds could be calculated from the pressure gradient. Strictly speaking, the gradient wind should be calculated, but for the purpose of this study it was assumed that the gradient wind approximates the geostrophic wind for the Lake Michigan area because spacing between observation points is too great to make a detailed analysis of the wind field to determine if there is a pronounced curvature in the streamlines.

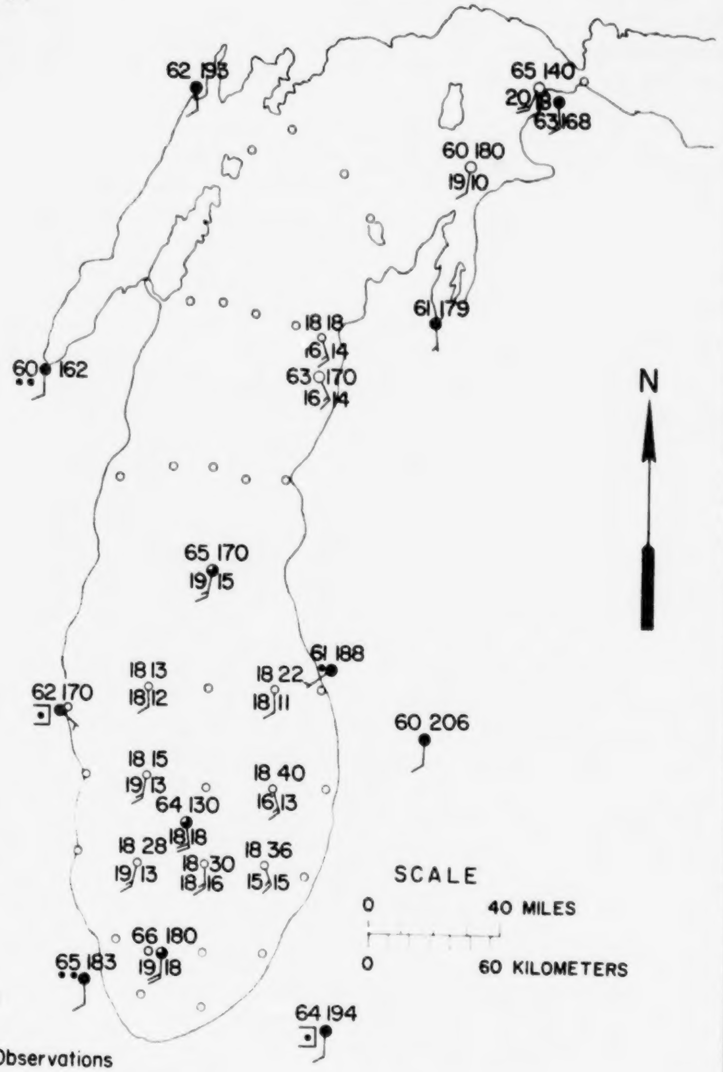
The geostrophic wind is defined as a wind that exists in frictionless straight flow when the pressure-gradient force balances the Coriolis force; in other words, a wind that flows parallel to straight isobars.

The gradient wind is the counterpart of the geostrophic wind in curved flow when the pressure-gradient force balances the Coriolis force and centrifugal force; in other words, a wind that flows parallel to curved isobars or streamlines.

The following discussion of results refers to the analysis of data for the period which has been most thoroughly studied -- September 1963.

The computer was used to prepare printout charts with the wind data entered on them. A sample chart including a few merchant ship observations is shown in Figure 9-6. Agreement between the wind directions observed from the buoy stations and those obtained from nearby vessels was excellent; differences in direction are usually in a range of 10 to 20 degrees. The fact that the ship observations are taken at a higher elevation than the buoy observations, and that the buoy winds are 6-hour averages, explains the lower speed values of the buoy winds as compared to ship winds.

Printout chart with buoy winds, ship winds, and observations at land stations for 06C September 2, 1963.


62 193
65 140
20 18
63 168
60 180
19 10
18 18
16 14
63 170
16 14
61 179
60 162
N
65 170
19 15
61 188
18 13
18 12
18 22
18 11
62 170
60 206
18 15
19 13
18 40
16 13
64 130
18 18
18 28
19 13
18 30
18 16
18 36
15 15
SCALE
0
40 MILES
0
60 KILOMETERS
66 180
19 18
65 183
64 194

LEGEND

NN DD dd vv	Buoy Station
NN	Number of Observations
DD	Coefficient of Variation of Speed
dd	Wind Direction
vv	Wind Speed
TT PPP ww dd vv	Ship Station
TT PPP ww	Land Station

GREAT LAKES - ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN PRINTOUT

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 9-6

In the investigation of the relationship of buoy and ship winds to geostrophic winds, data were examined for station 18 in the southern basin of Lake Michigan, and for station 41 in the northern basin. Ship observations were selected for points as close to these stations as possible. For each of the two stations the data were divided into two groups according to stability of the air mass. For this purpose, an air mass with a lapse rate less than 6°C between water surface and the 850-millibar (mb) was considered to be stable; and an air mass with a corresponding lapse rate of 6°C or more was classified as unstable. For estimating the lapse rates, the surface temperature was assumed to be approximated by surface water temperatures obtained from municipal water intake records; temperature at the 850-mb level was interpolated from meteorological records. The 850-mb level is approximately 4,000 feet above the Lake.

Table 9-2 shows the average ratios of buoy and ship wind speeds to geostrophic winds over Lake Michigan for the month of September 1963. In all cases shown, the ratios are less at station 41 than at station 18, for reasons that have not been determined. The ratios are larger for a steep lapse than for a small rate. This is to be expected, since there is more mixing between the lower and middle layers of the atmosphere in unstable than in stable situations. The range of values shown for steep lapse rates is 0.529 to 0.771, and for small lapse rates 0.481 to 0.585.

Table 9-3 shows the average clockwise deviation of buoy and ship wind directions from geostrophic wind directions over Lake Michigan for the same period. In all cases shown, the deviation at station 41 is consistently greater than at station 18. For steep lapse rates the deviation of buoy and ship winds from geostrophic winds is less than for small lapse rates. The range of values shown for steep rates is 14° to 42° and for small lapse rates 39° to 57°, respectively.

Statistical tests were made to determine whether the variations in the relationship between observed and geostrophic winds for stations 18 and 41 and for small and steep lapse rates were significant. The tests were inconclusive for the difference between stations, but showed that there is a significant difference in the wind relationship for small and steep lapse rates.

Charts for the current records, constructed on the same basis and for the same time periods as the wind charts, are not very enlightening as to relationship of Lake currents to concomitant winds. The rotary currents shown in Figure 9-7 (plotted from 6-hour means) frequently dominate the record, but the phase of rotation may vary with depth at one station and with horizontal distance at one depth. Numerical filters have been used in an attempt to eliminate this inertial

TABLE 9-2

RATIO OF BUOY AND SHIP WIND SPEEDS TO GEOSTROPHIC WIND SPEEDS OVER LAKE MICHIGAN FOR SEPT. 1963

STEEP LAPSE RATE				SMALL LAPSE RATE			
Buoy		Ship		Buoy		Ship	
#18	#41	#18	#41	#18	#41	#18	#41
0.629	0.529	0.771	0.716	0.481	0.385	0.589	0.523

TABLE 9-3

AVERAGE DEVIATION OF BUOY AND SHIP WIND DIRECTIONS FROM GEOSTROPHIC WIND DIRECTIONS OVER LAKE MICHIGAN FOR SEPT. 1963

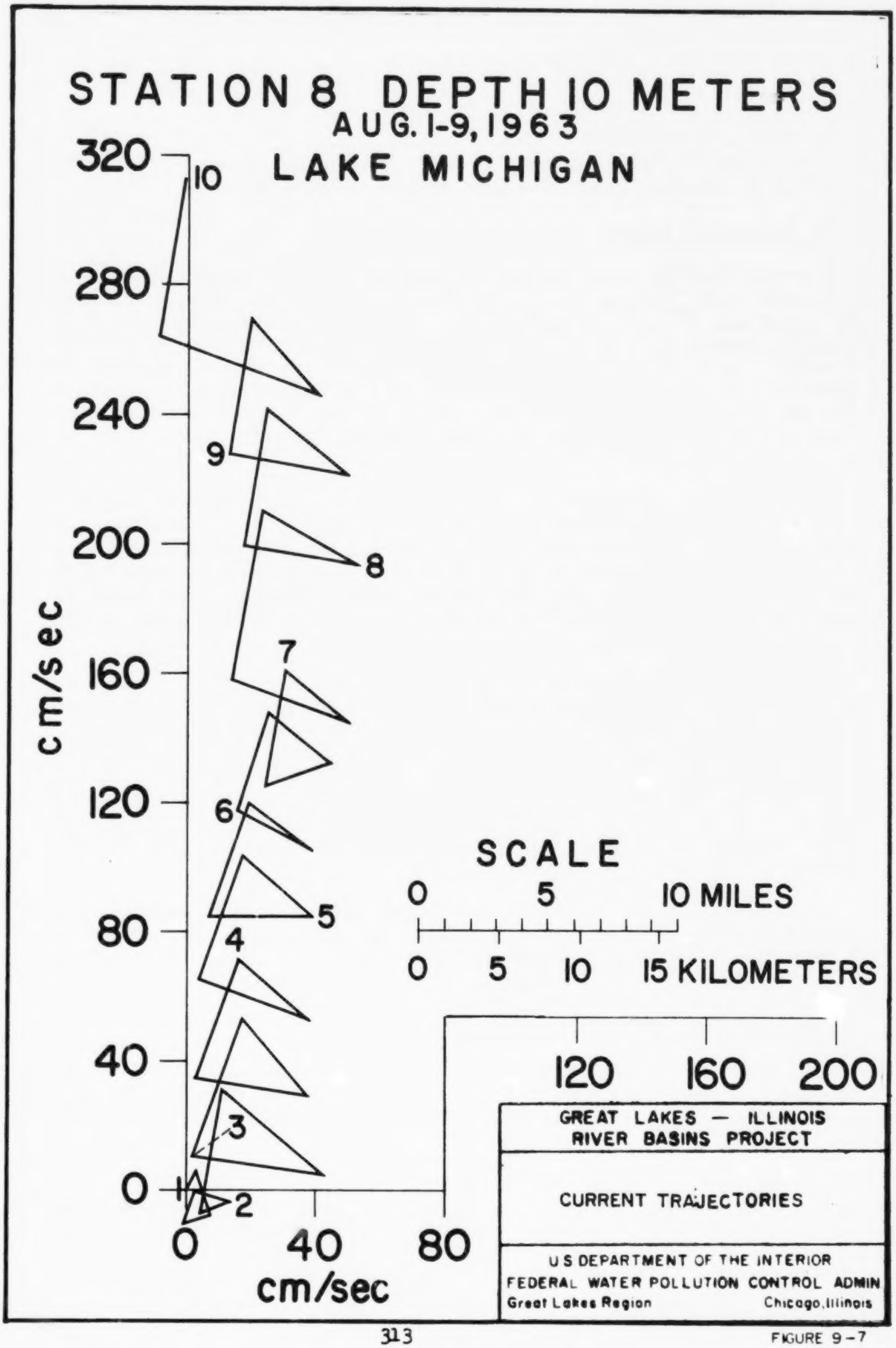
STEEP LAPSE RATE				SMALL LAPSE RATE			
Buoy		Ship		Buoy		Ship	
#18	#41	#18	#41	#18	#41	#18	#41
14°	26°	17°	42°	42°	57°	39°	45°

TABLE 9-4

WINDS - STATION 5, AUGUST 1963

HISTOGRAM

DIRECTION IN DEGREES	SPEED AVERAGE IN KNOTS					NUMBER
	7	19	32	45	58	
0	51	81	30	6	0	168
30	71	91	15	0	0	177
60	67	40	0	1	0	108
90	105	32	5	1	1	144
120	130	15	1	0	1	147
150	121	21	0	0	1	143
180	138	44	7	1	0	190
210	163	51	5	1	2	222
240	103	32	1	0	0	136
270	78	14	1	0	0	93
300	38	10	5	4	0	57
330	69	18	14	4	0	105
TOTALS	1,134	449	84	18	5	1,690



GREAT LAKES — ILLINOIS RIVER BASINS PROJECT

CURRENT TRAJECTORIES

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 9-7

period from a few short samples of data, but further study is needed to understand the significant features of the filtered data.

Lake Breeze Phenomenon

At times the lake breeze phenomenon is pronounced along the shores of Lake Michigan. The wind data obtained from the buoys on Lake Michigan help to clarify some details of the phenomenon. An example of the lake breeze is given here for August 20 and 21, 1963. On those days a large weak high was centered over the Ohio Valley with a weak pressure gradient extending over the southern part of Lake Michigan, northern Illinois, southern Wisconsin, and lower Michigan. Figures 9-8 and 9-9 show the weather charts for 12C (noon, Central Standard Time) August 20 and 21.

At 12C on both days, temperatures at the land stations near the southern Lake Michigan shores ranged from around 72°F to 85°F. The Lake temperature on August 20 was 63°F at Chicago and 50°F at Muskegon. On August 21, Lake temperature was 56°F at both Chicago and Muskegon. With the Lake cooler than land the air in contact with the water would be expected to be cooler than the air over land, thus making ideal conditions for a lake breeze.

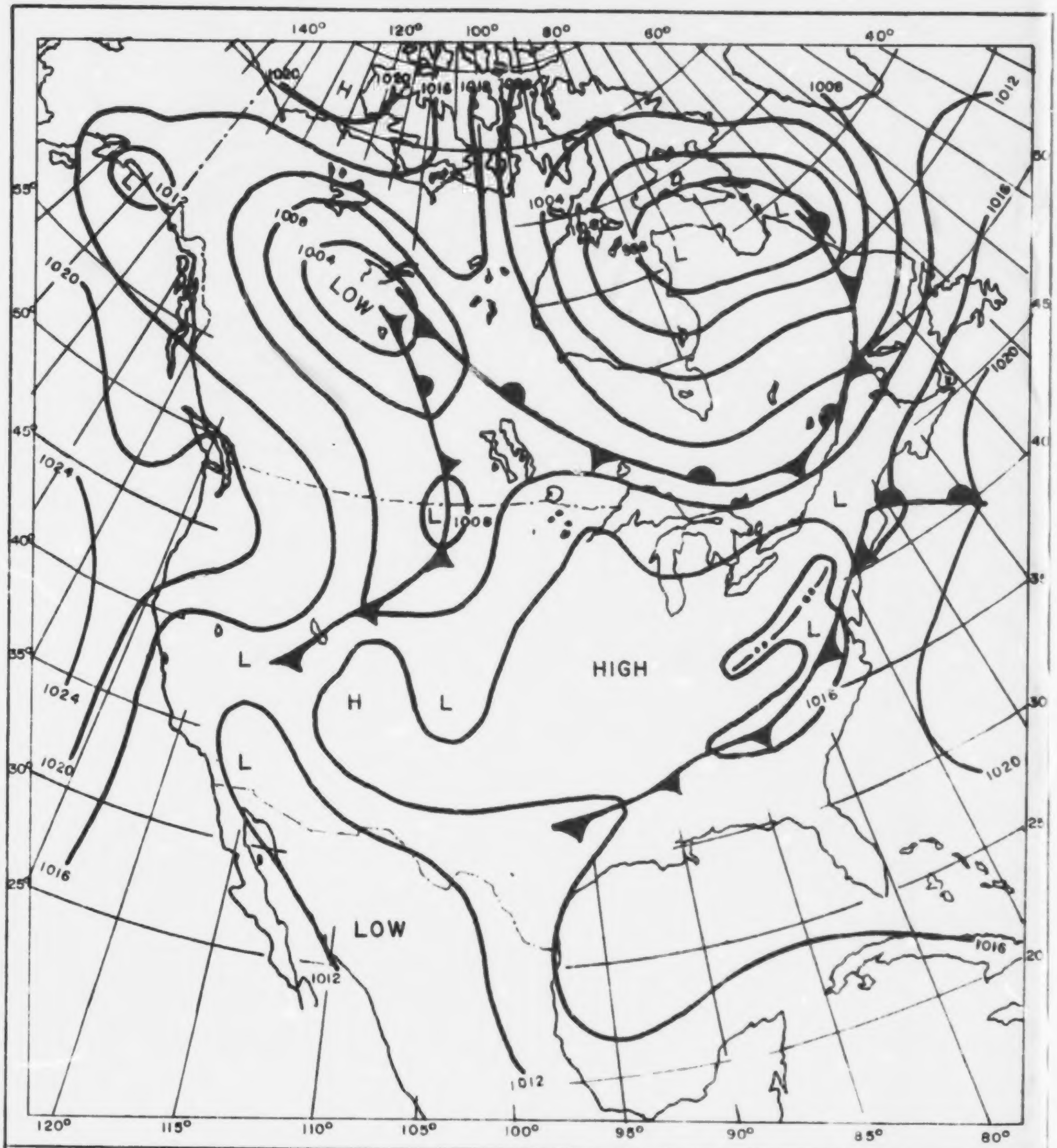
Two-hour envelopes of wind direction are presented in Figures 9-10 and 9-11 for stations 8 and 18 on August 20 and 21. At station 8 on the envelope for the first day, the wind is blowing from the southwest through west until 10 o'clock. Then it shifts to southeast and remains from that direction until 22C when it shifts to the southwest and west for the rest of the night. The cycle is repeated on the second day but the shift back to the southwest begins at about 18C rather than 22C. Station 18, Figure 9-11, shows the same type of cycle of wind directions as station 8 for the two days.

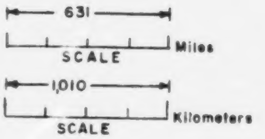
The relationship between geostrophic and observed winds gives a basis for a method of forecasting winds over the Great Lakes. Unfortunately, the relationship between winds and lake currents is not as straightforward.

A Comparison of Lake Wind to Land Wind

Wind data at Lake station 8 were compared to those from Midway Airport, Chicago, Illinois for the month of September 1963. Six-hour average winds for the two locations were compared over the 1-month period.

Figure 9-12 shows the directional relationship between the stations. Disregarding occasional periods of calm, the absolute value (without regard to whether clockwise or counterclockwise) of the


140°
120°
100°
80°
60°
40°
1020
H
1020
1016
1016
1020
1008
1012
L
1012
55°
1020
50°
45°
1024
40°
35°
1024
30°
1020
25°
1016
1008
1004
LOW
L
1008
L
H
L
HIGH
L
L
1016
1004
1000
996
L
L
1016
1020
1020
1016
LOW
1012
1012
120°
115°
110°
105°
100°
95°
90°
85°
80°

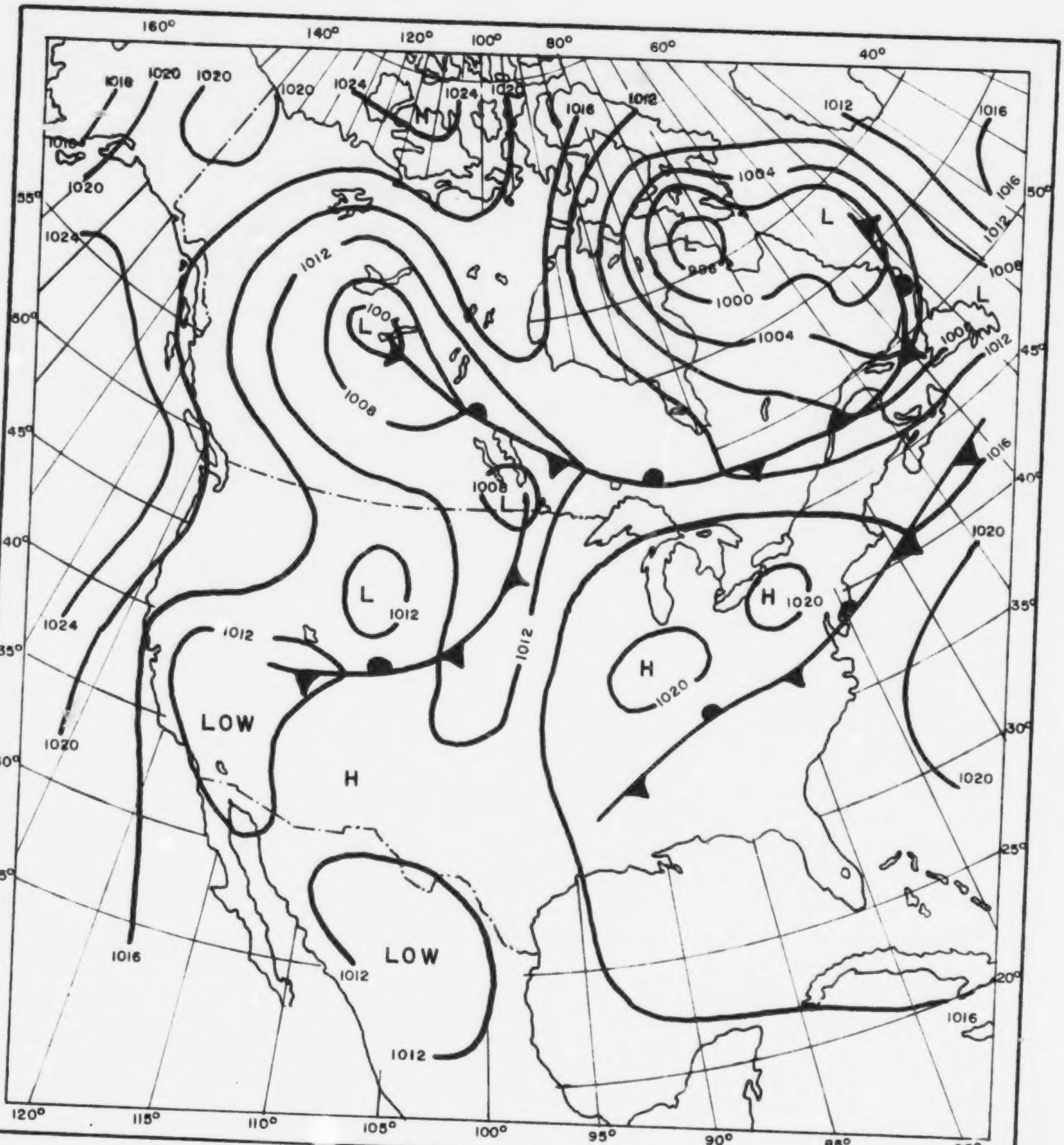

631
SCALE
Miles
1,010
SCALE
Kilometers

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SURFACE WEATHER MAP AT 1200 CST.
TAKEN FROM DAILY WEATHER MAP
U.S. WEATHER BUREAU AUGUST 20, 1963

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 9-8


160°
140°
120°
100°
80°
60°
40°
1016
1020
1020
1020
1024
H
1024
1020
1016
1012
1012
1016
1016
1020
1024
1004
L
996
1000
1004
L
1012
1008
L
1012
1004
L
1008
1008
L
1008
1012
1016
1020
L
1012
1012
H
1020
H
1020
1012
LOW
H
1024
1020
1016
LOW
1012
1012
1020
1016
55°
50°
45°
40°
35°
30°
25°
20°
120°
115°
110°
105°
100°
95°
90°
85°
80°

631
Miles
SCALE
1010
Kilometers
SCALE

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SURFACE WEATHER MAP AT 1200 C.S.T.
TAKEN FROM DAILY WEATHER MAP
U.S WEATHER BUREAU AUGUST 21, 1963

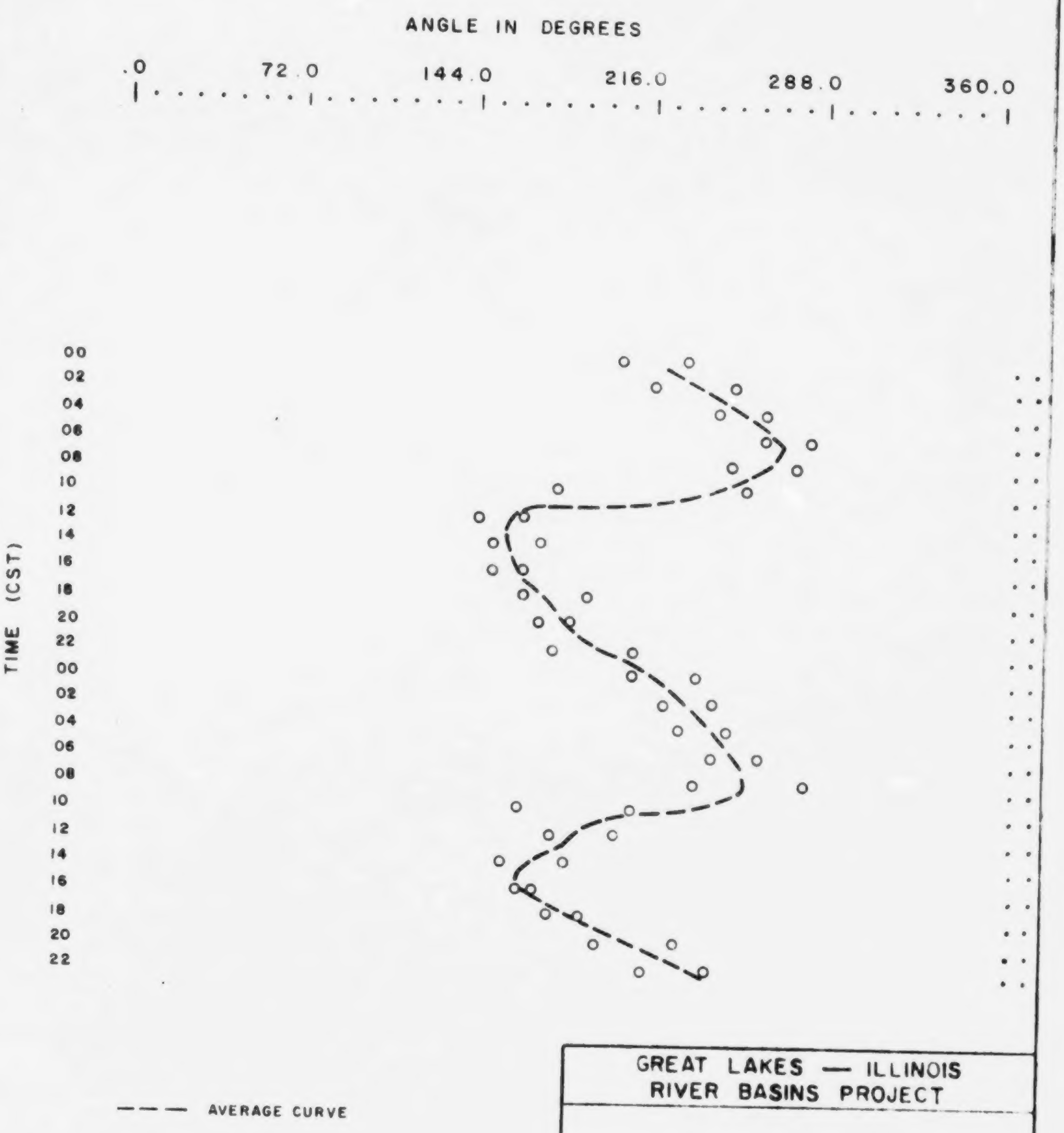
U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 9-9

TWO HOUR SPEED-ANGLE ENVELOPE

AUGUST 20-21,1963

FILM - 20066 STA 8 DEPTH 0 TIME INTERVAL - 20



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TWO HOUR SPEED-ANGLE ENVELOPE

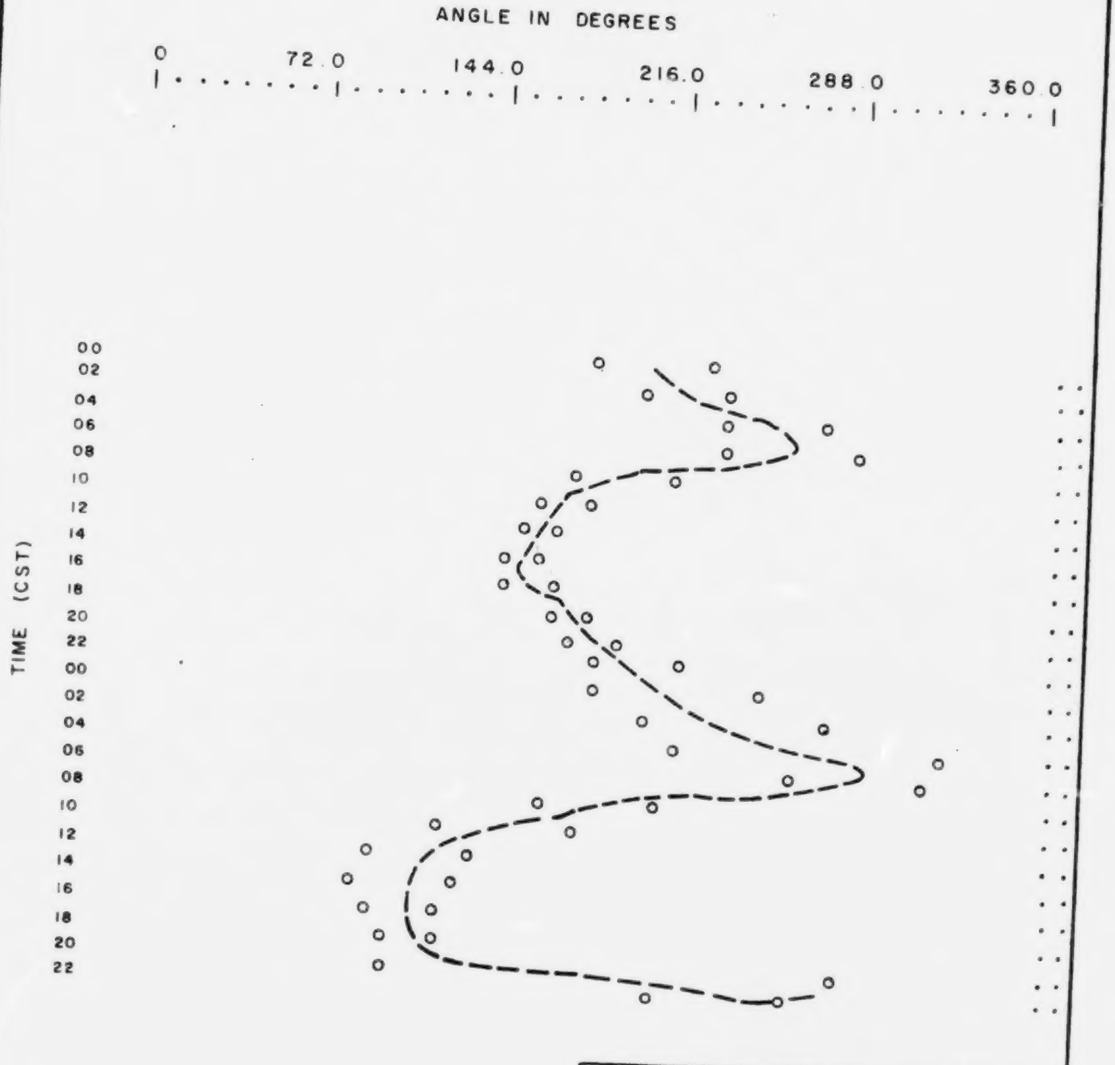
U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 9-10

TWO HOUR SPEED-ANGLE ENVELOPE

AUGUST 20-21,1963

FILM-20170 STA. 18 DEPTH 0 TIME INTERVAL - 20

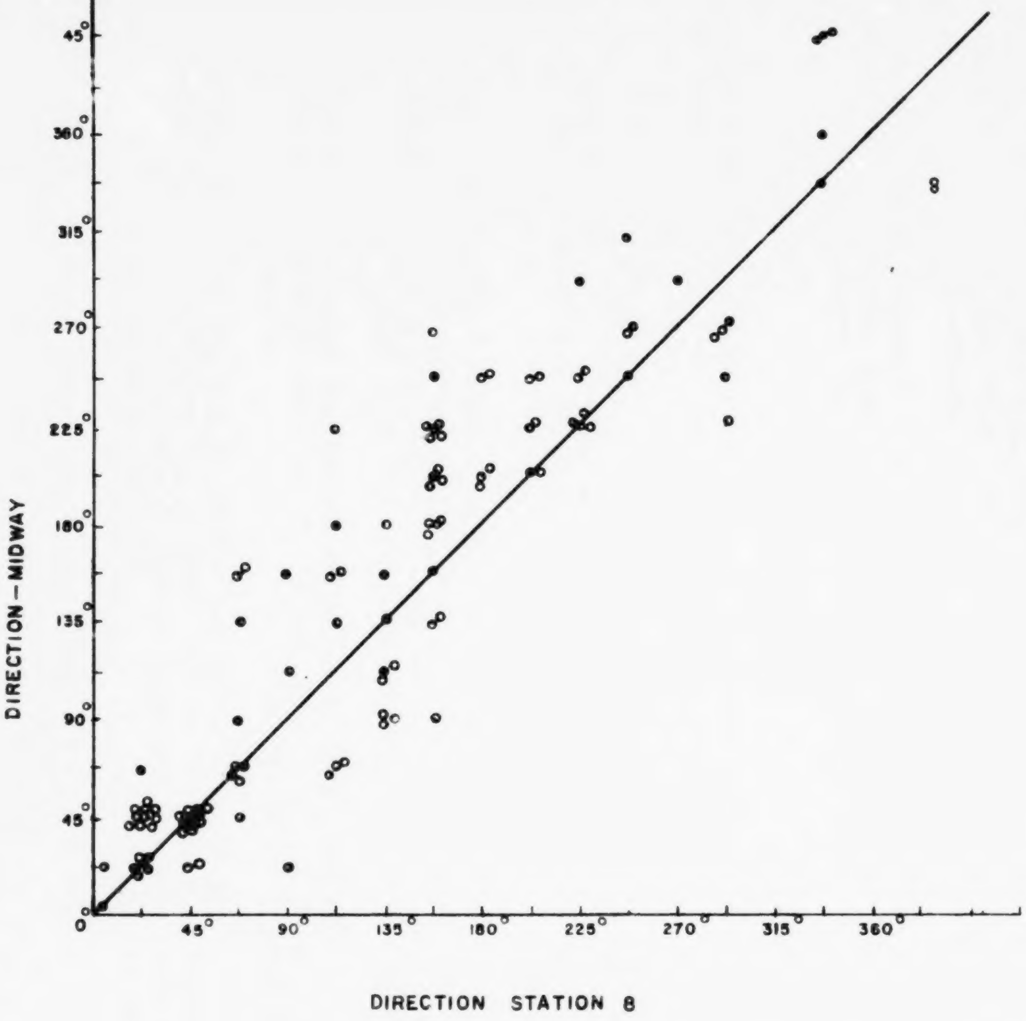


GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TWO HOUR SPEED-ANGLE ENVELOPE

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 9-11



6-Hour Average Direction
September, 1963

GREAT LAKES – ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN vs.
SHORE WIND DIRECTION

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 9 – 12

deviations averaged 32 degrees. The algebraic average deviation, considering a clockwise deviation of lake wind to land wind as positive, was minus 17 degrees; that is, on the average the lake wind direction was deflected counterclockwise from that over Midway Airport. As a further indication of prevailing conditions during the month examined, the deviation of lake wind to land wind was either zero or counterclockwise some 80 percent of the time.

Wind speeds during September were higher over the Lake than over land, as expected for summer and fall. The reverse is probably true for late winter and spring, but no Lake records are available. The average wind speed at Midway was 16.0 km/hr (10.0 mph) and at station 8 it was 19.6 km/hr (12.1 mph), or 17 percent higher over the Lake. Figure 9-13 indicates close agreement in the lower speed to about 10 km/hr and the difference widens until 40 km/hr where there appears to be a break. There are too few numbers beyond 40 km to estimate the trend.

Although winds do not alter current directions in mid-lake during the summer period, there is a relationship between wind speed and increased current speeds, even at great depths (Verber, 89).

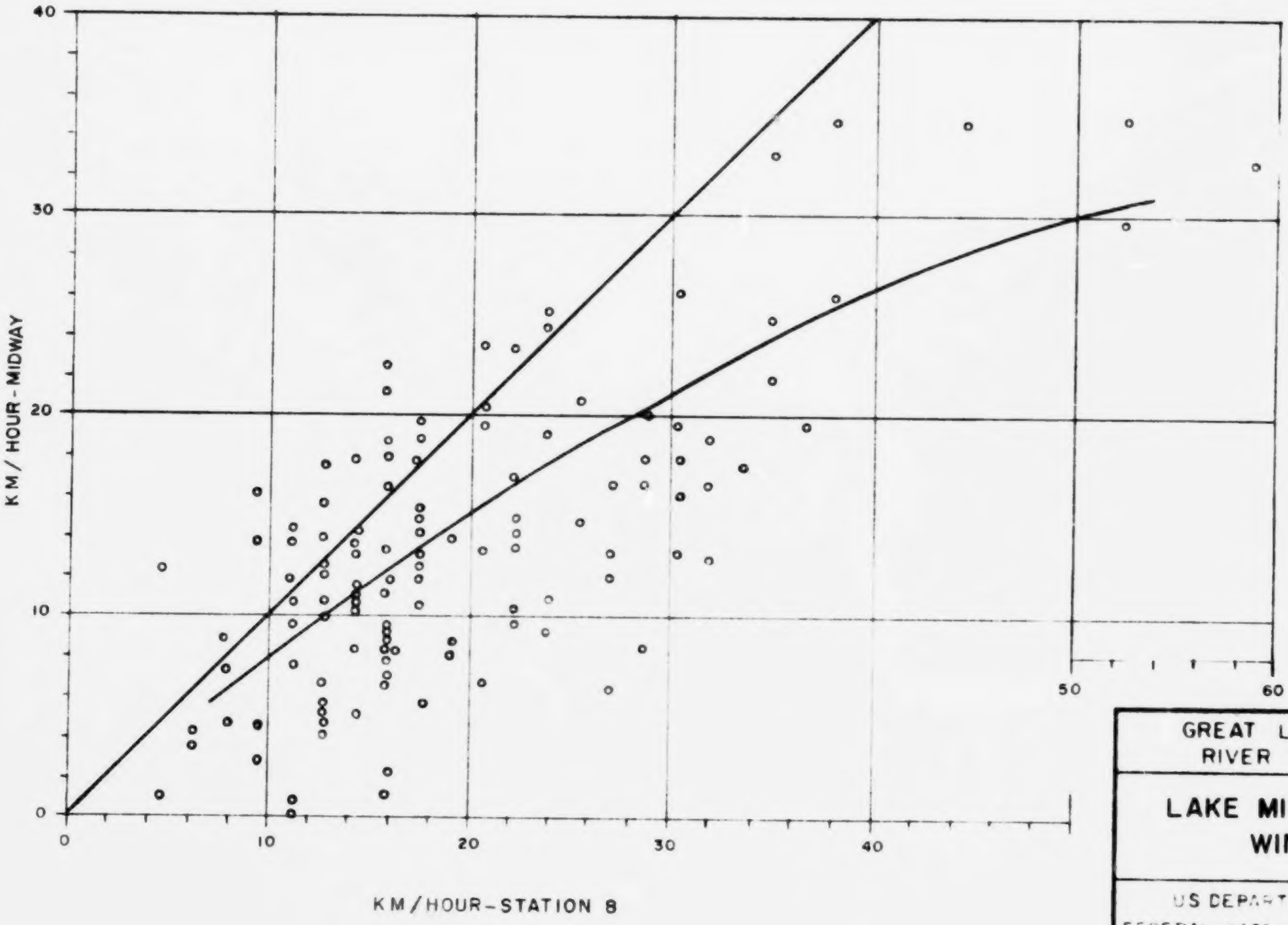
Wind Spectra

This section covers the wind spectra computed from Lake Michigan wind records collected during the summers of 1963 and 1964. Table 9-5 summarizes the wind spectra analyzed. In this table each station has listed: the film number of the record, the length of each record, the orientation of the axis for the velocity component computation, and whether or not the station is near the shore. Speed spectra calculations were not made after test cases showed that estimates were unreliable.

The following stations from the summer of 1963 showed a diurnal peak around 24 hr in one or both of the velocity components: Stations 1, 8, 10, 13, 15, 20, and 41. Stations 5 and 30 have no significant peaks. Station 40 (Summer 1964) has a diurnal peak.

The semidiurnal oscillation is evident in records from stations 8, 10, 13, 15, 20, 30, 40, and 41. Figure 9-14, station 13, illustrates an example of wind spectra.

Long period oscillations around 115 hrs are evident and may represent some kind of average frequency of meteorological disturbances. Whether they are physically present is still unknown, but they fit with the energy peaks.



6 Hour Average Wind Speeds
September, 1963

Midway - Ave. 16.0
Sta. 8 - Ave. 19.6

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

LAKE MICHIGAN vs SHORE
WIND SPEEDS

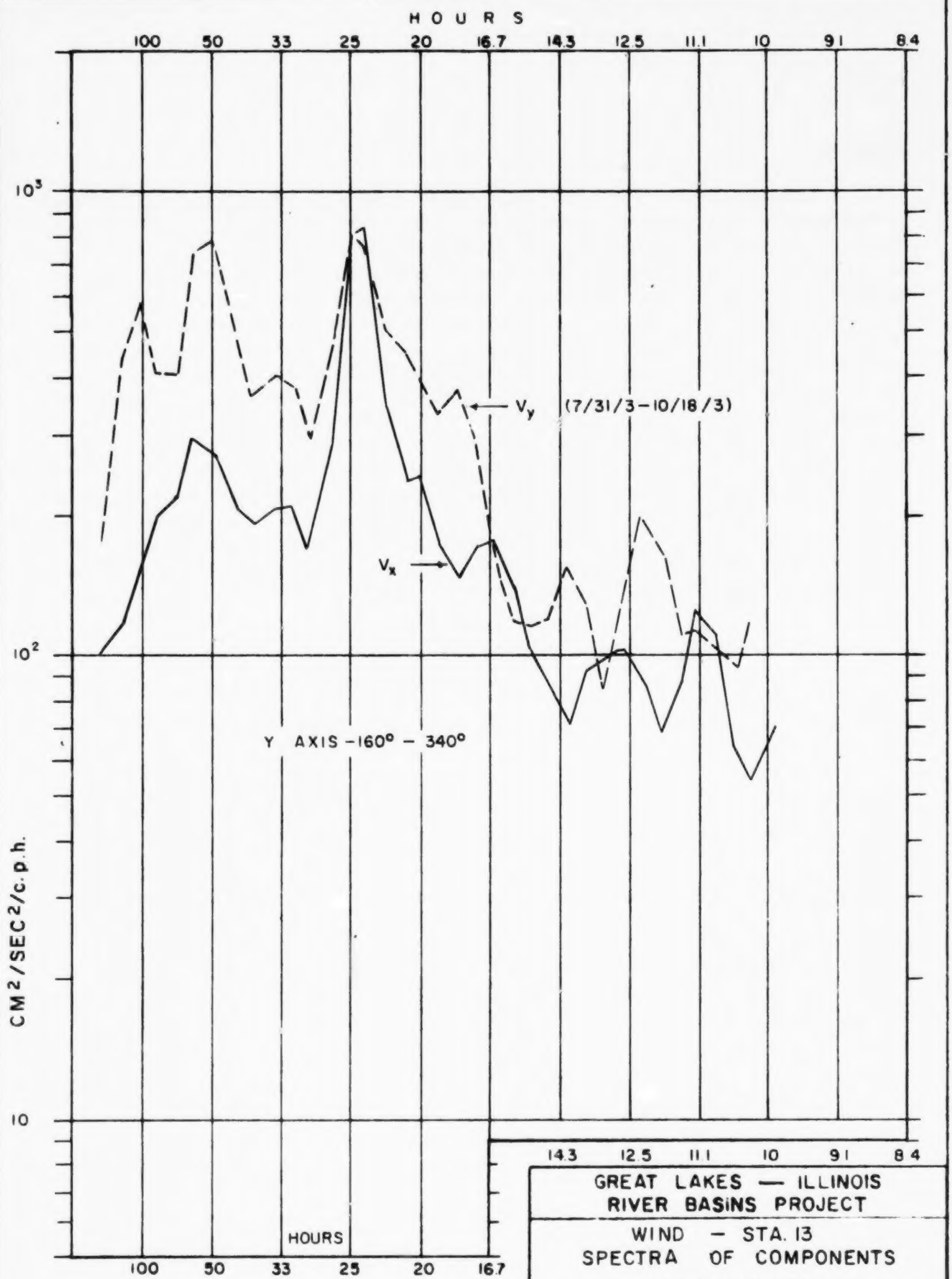
US DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 9 – 13

TABLE 9-5

LAKE MICHIGAN WIND SPECTRA DATA

STA-TION	FILM NO. 200-	DATES OF SPECTRAL RECORDS START	DATES OF SPECTRAL RECORDS END	VELOCITY SPECTRA AXIS ORIENTATION (Y AXIS)	NEARSHORE STATION	OFFSHORE STATION
01	038	07/24/63	09/04/63	0-180		x
05	333	05/12/64	07/06/64	30-210		x
08	066	07/30/63	10/16/63	30-210		x
10	070	08/16/63	10/17/63	170-350		x
13	069	07/31/63	10/18/63	160-340		x
15	068	08/05/63	10/17/63	0-180		x
20	141	08/04/63	11/07/63	0-180		x
30	342	04/19/64	07/04/64	0-180		x
40	345	04/19/64	07/03/64	30-210		x
41	169	08/22/63	11/05/63	0-180	x	



GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND – STA. 13
SPECTRA OF COMPONENTS
LAKE MICHIGAN

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

NO. OF OBSERVATIONS – 5658

FIGURE 9-14

Summary

The meteorological studies have revealed relationships between geostrophic winds and observed winds over Lake Michigan; and between winds over the Lake and winds at adjacent land stations. This provides a basis for forecasting the speed and direction of wind at desired specific locations over the Lake. Unfortunately this cannot, with present knowledge, be translated into forecasts of water current velocity. While there is no doubt that the wind is the primary force causing motion of Lake Michigan water, the relationship is a complex one, the water motion being modified by such factors as variations in atmospheric pressure on the Lake surface and the earth's rotation. Once set in motion by primary wind forces, the water velocity at a particular place and time will be a function of antecedent conditions perhaps far removed in time, and will exhibit internal wave patterns corresponding in periodicity to seiches and the Lake's inertial period. It is believed that further study can yield a solution which will permit formulation of a mathematical model incorporating all of these factors, and make possible the forecasting of Lake currents.

CHAPTER 10

CORRELATION OF WIND, CURRENT, AND TEMPERATURE IN SUMMER

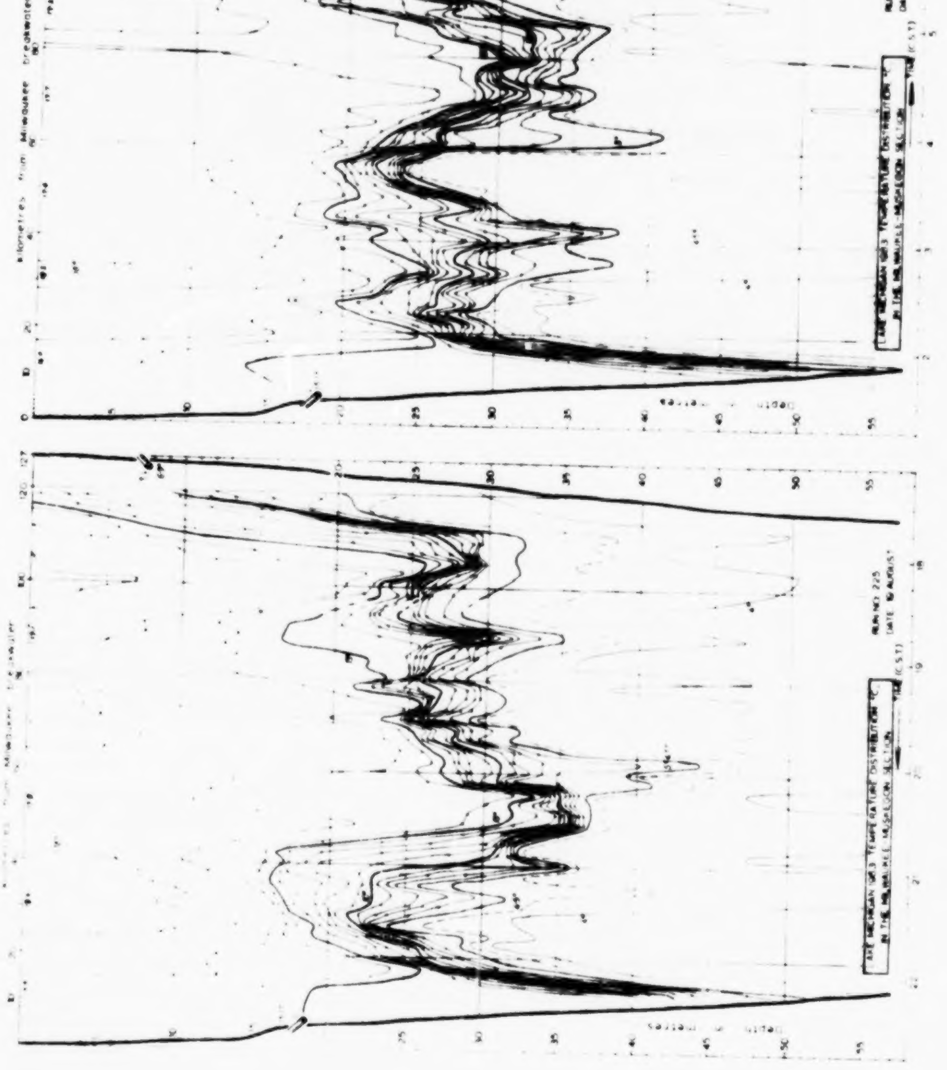
by

Clifford H. Mortimer and James L. Verber

During the Project studies in the summer of 1963 the University of Wisconsin was conducting specific internal wave studies in the region between Milwaukee, Wisconsin and Muskegon, Michigan. These studies, combined with Project studies, shed new light on the relationships among wind, currents, and temperature.

At the University of Wisconsin, Dr. C. H. Mortimer was given a "Visiting Professorship" for the opportunity to test hypotheses concerning internal waves and associated water movement in central Lake Michigan. This work was supported by an Office of Naval Research contract, Nonr-1202 (22), and some results of current measurements at midlake anchor stations were outlined in Chapter 6. In addition, with facilities provided by the Grand Trunk Western Railroad Company, temperature distribution was measured from the Company's vessels on 80 crossings between July 14 and August 30, 1963. Apart from occasional gaps due to change of vessel or instrument loss, the 127-km long section was monitored on consecutive crossings with bathythermograph (BT) casts every 2 km.

During the whole period the thermocline showed oscillations in depth, often quite large, and often combined with or following strong upwelling on one shore and downwelling on the other shore after wind disturbances. For instance, two major storms, from the north on August 13 and 17 (see Figures 10-5 and 10-6), produced a strong downward tilt of the thermocline on the western shore and upwelling on the eastern shore which persisted for several days. The latter storm also generated internal waves of large amplitude, illustrated by two consecutive temperature sections in Figure 10-1. These pictures are not, of course, synoptic, as the ferries take roughly six hours to cross the Lake; but the standing nature of the internal waves is made evident in Figures such as 10-1 by the fact that on consecutive runs the ferries normally cross the midlake point at intervals of about 8 hours, i.e., approximately one-half of the local inertial period (17.55 hours). Internal standing waves of near-inertial period should, therefore, show a change in sign of wave slope near the midlake position and this was frequently observed on successive crossings (Figure 10-1). The change in sign of the thermocline slope at about 70 km from Milwaukee suggests that there was a node in that region. This is confirmed and more strikingly



(Mortimer, unpublished, April, 1967)

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TEMPERATURE DISTRIBUTION
BETWEEN MILWAUKEE, WIS.
AND MUSKEGON, MICH.

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

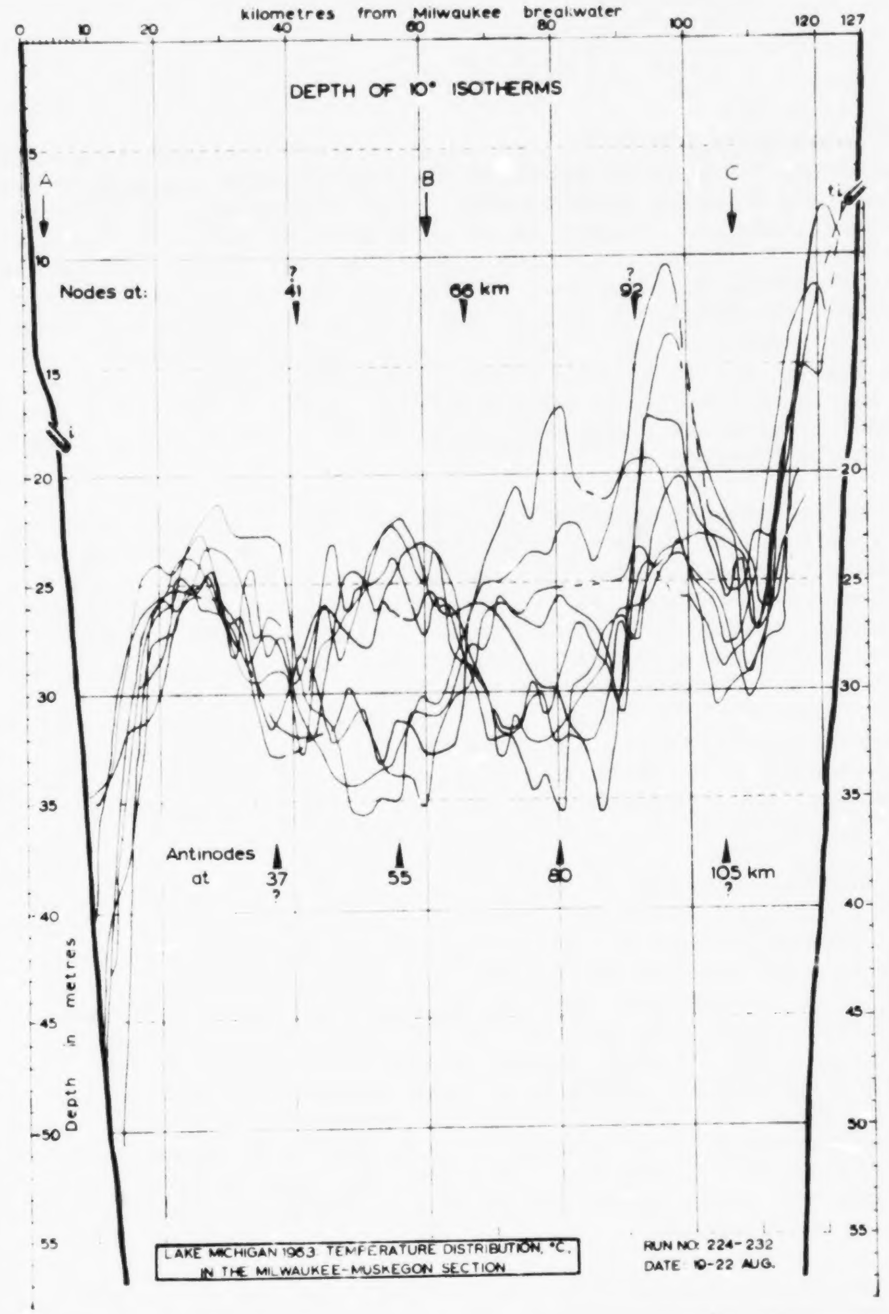
FIGURE 10-1

demonstrated in Figure 10-2, in which the 10° isotherm (representing approximately thermocline depth) is plotted for nine consecutive crossings over the interval August 19-22. The Figure shows a definite and persistent node in midlake at 66 km from Milwaukee, with less clear indications of at least two other nodes. The most likely interpretation of this Figure is in terms of a combination of transverse standing waves of several nodalities, with first and third predominating and perhaps a fifth also present. Odd nodalities must have been preferred, because of the way in which the wind stress tilted the thermocline down on one shore and up on the other; and the midlake nodes of each wave probably coincided to give the clear picture at 66 km. Coincidence elsewhere would not be expected.

Having demonstrated the generation of a large amplitude transverse standing wave pattern, it will be helpful to recapitulate briefly Mortimer's 1963 predictions (54) concerning the nature of internal waves in central Lake Michigan, as illustrated in Figures 10-3 and 10-4, for rectangular models of constant depth, rotating counterclockwise. The wave surfaces shown in those Figures can be envisaged, either as a water surface or as a thermocline interface between two homogeneous layers of differing density, in which case the (highly) generalized currents, associated with the waves, are shown for the lower layer (hypolimnion). The corresponding currents in the upper layer will be exactly opposed in direction; and the speed ratio will be the inverse of the depth ratio of the two layers.

In a narrow channel (Figure 10-3, upper part) a Kelvin wave is dominant, and this is also true near the shore in the other wide-channel models. The currents are constrained to run parallel to the shore, and the response to rotation takes the form of an exponential decrease in wave amplitude and current speed along a line normal to the shore. For the internal Kelvin wave case in Lake Michigan, this amplitude falls to a negligible value 10 km or so away from the shore. Internal Kelvin waves are, therefore, essentially shorebound. At greater distances offshore, where the constraints of the boundaries can no longer be "felt", the response to rotation, in a semi-infinite sea of constant depth, Figure 10-3, lower part, is a Sverdrup wave, in which the wave crests are horizontal but in which the currents rotate (clockwise in the northern hemisphere).

Lake Michigan, however, is bounded; and just as in lakes small enough for rotational effects to be neglected, seiches are set up by wave reflection from opposing shores. In the special case, only possible in an infinitely long channel (Figure 10-4, upper part), two equivalent Sverdrup waves, of equal amplitude, traveling in opposite directions normal to the side of the channel, produce a standing wave



LEGEND

A - Sta. 17, 11.5 Km. North of Ferry Track

B - MV "Cisco," 12 Km. North of Ferry Track

C - Sta. 20, 6.5 Km. South of Ferry Track

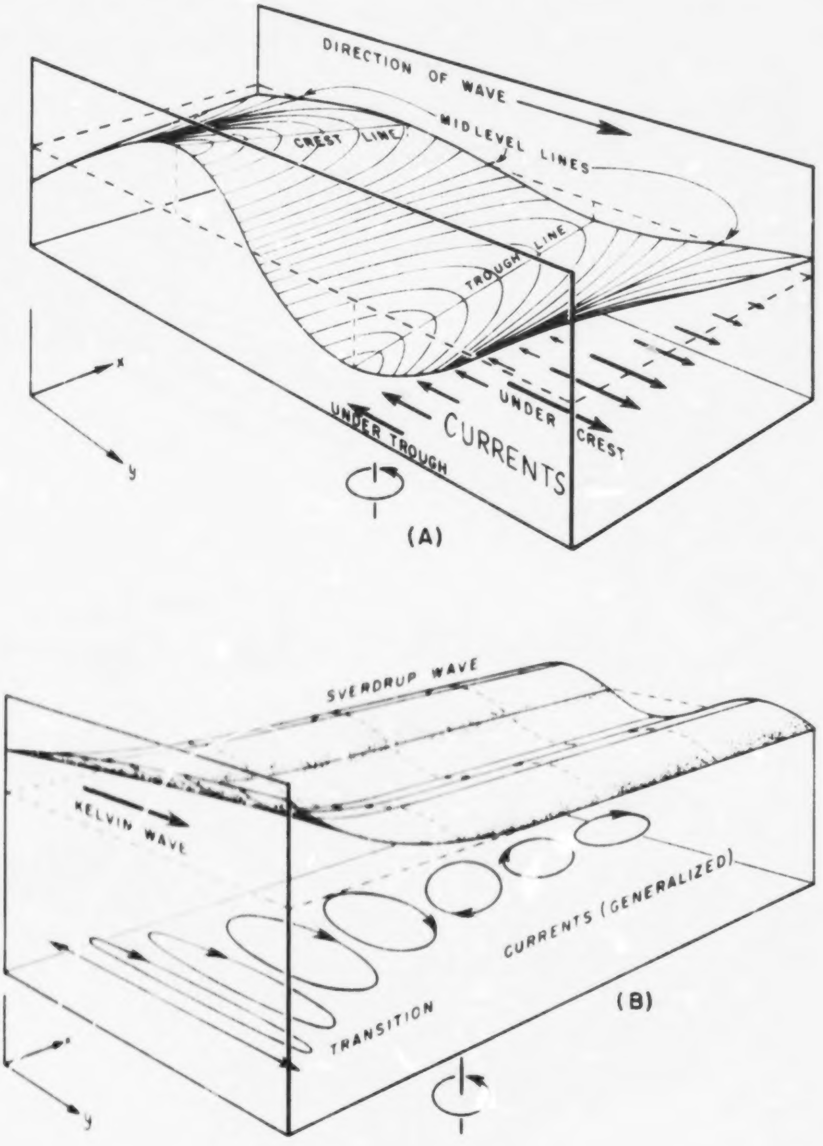
(Mortimer unpublished, April, 1967)

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

DISTRIBUTION of 10° ISOTHERM
MILWAUKEE to MUSKEGON

U.S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 10-2


DIRECTION OF WAVE
MIDLEVEL LINES
CREST LINE
TROUGH LINE
x
y
UNDER TROUGH
CURRENTS
UNDER CREST
(A)
SVERDRUP WAVE
KELVIN WAVE
CURRENTS (GENERALIZED)
TRANSITION
x
y
(B)

LEGEND

A. - Qualitative Representation of A Single Kelvin Wave
B - Qualitative Representation of Part of A Semi-Infinite Rotating Sea with A Kelvin Wave

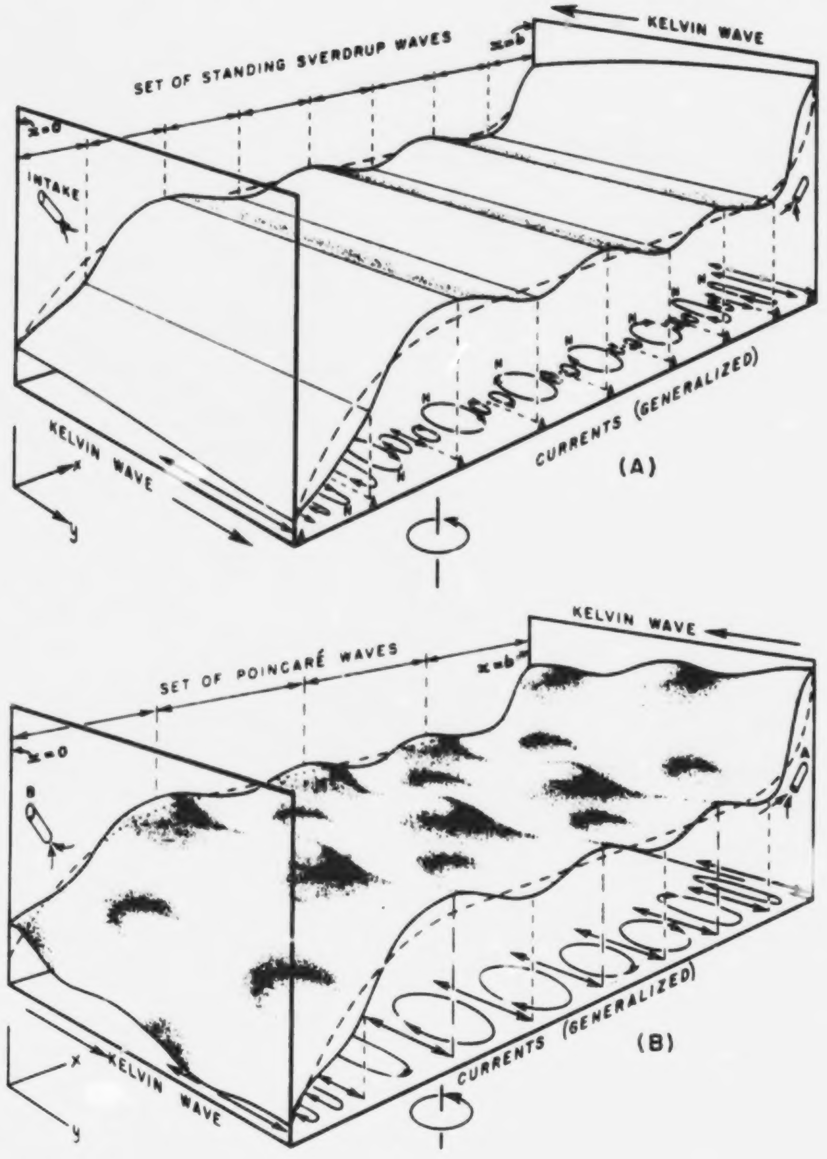
GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

QUALITATIVE REPRESENTATION of
KELVIN and SVERDRUP WAVES

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

After Mortimer, 1963(54)

FIGURE 10-3


KELVIN WAVE
SET OF STANDING SVERDRUP WAVES
x=b
x=0
INTAKE
KELVIN WAVE
x
y
CURRENTS (GENERALIZED)
(A)
KELVIN WAVE
SET OF POINCARÉ WAVES
x=b
x=0
B
A
x
KELVIN WAVE
y
CURRENTS (GENERALIZED)
(B)

LEGEND

A.- Qualitative Representation of Transverse Standing Waves with Sverdrup and Kelvin Waves

B.- Qualitative Representation of Standing Poincaré Waves

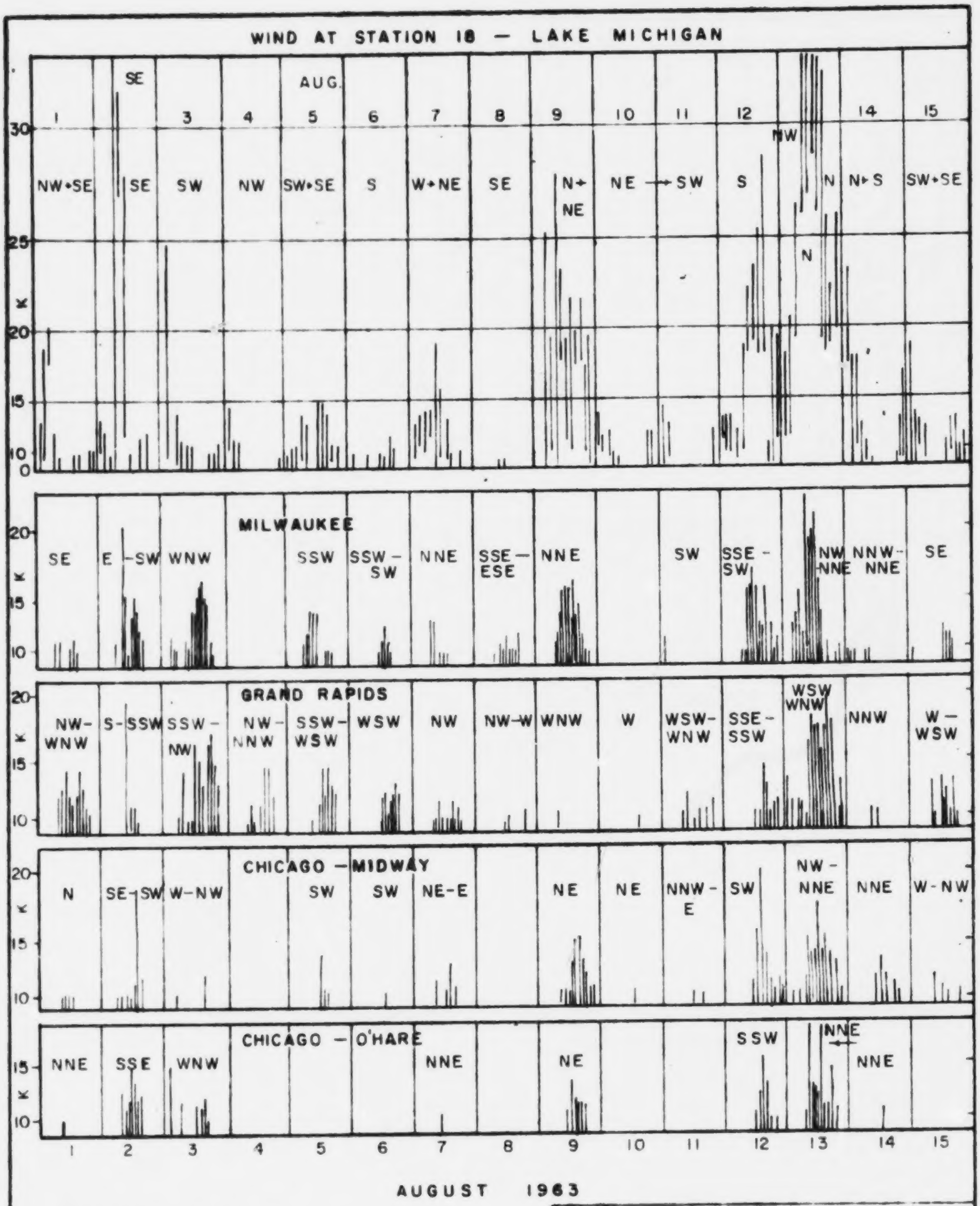
After Mortimer, 1963 (54)

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

TRANSVERSE STANDING, KELVIN, SVERDRUP and POINCARÉ WAVES

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 10-4



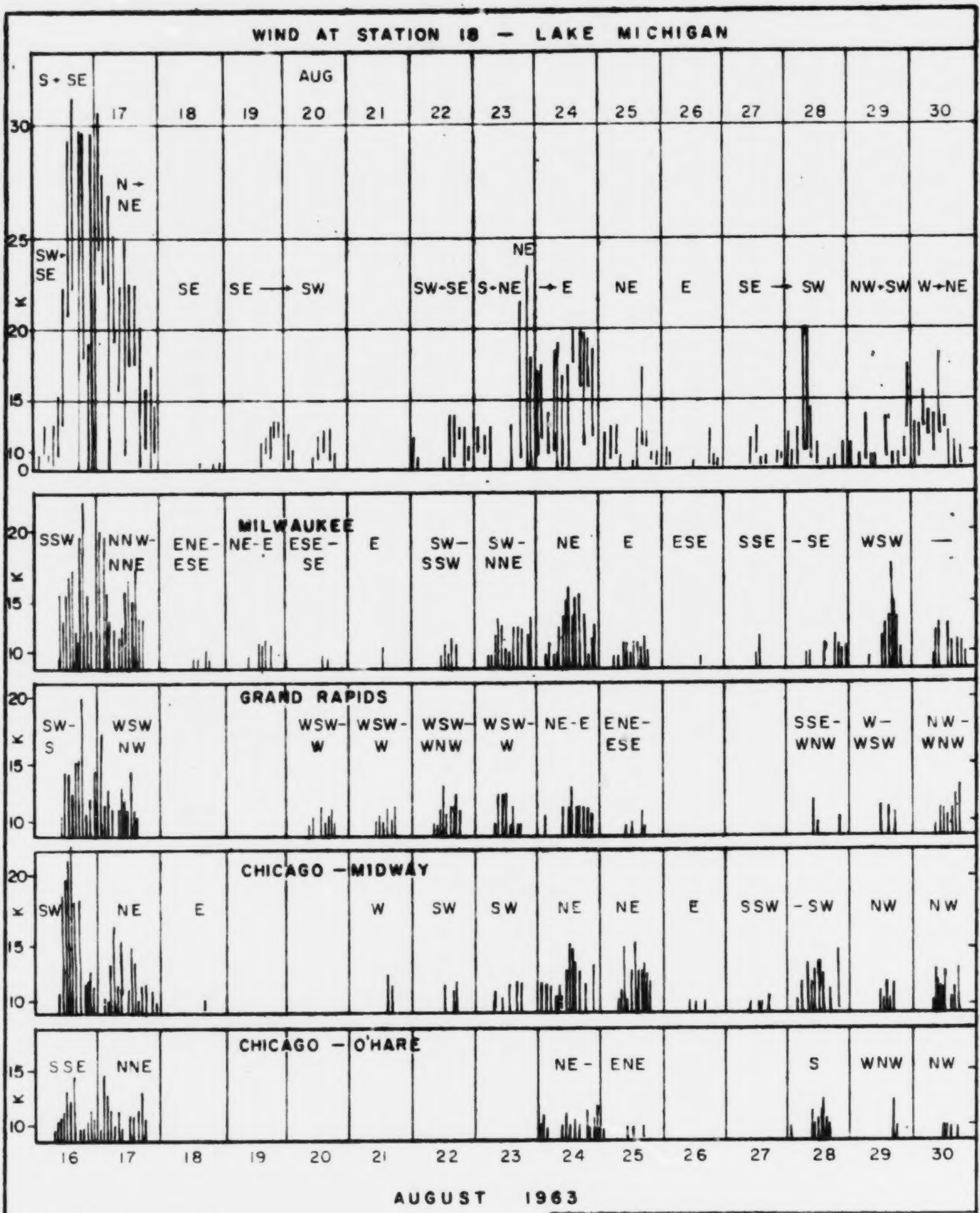
SPEED IN KNOTS
LAKE WIND - 2 HOUR ENVELOPES
LAND WIND - HOURLY
ONLY SPEEDS OVER 9 KNOTS WERE
CONSIDERED AND PLOTTED ON A SQUARE - LAW
SCALE TO APPROXIMATE WIND STRESS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

COMPARISON OF LAKE
AND LAND WIND SPEEDS

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 10-5



SPEED IN KNOTS
LAKE WIND - 2HOUR ENVELOPES
LAND WIND - HOURLY
ONLY SPEEDS OVER 9 KNOTS WERE
CONSIDERED AND PLOTTED ON A SQUARE-LAW
SCALE TO APPROXIMATE WIND STRESS

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

COMPARISON OF LAKE
AND LAND WIND SPEEDS

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 10-6

system with horizontal wave crests running along the length of the channel. Because of the boundary condition, that the transverse component of flow must always be zero at the shores, only a discrete number of waves can develop across the channel.

If the channel is not infinitely long but has ends, then Sverdrup wave reflection will occur at these boundaries also; and a second discrete set of standing waves will be set up, this time along the channel and again meeting the boundary condition that there shall be no flow normal to the ends. The combination of this longitudinal set with the transverse set results in a cellular pattern of standing waves (Poincaré waves), and the dimensions of the cells are determined by the wave lengths in the longitudinal and transverse directions. A portion of such a system, representing the central part of Lake Michigan, is shown in the lower part of Figure 10-4. This presents a model of thermocline topography and also indicates part of a long shorebound Kelvin wave close to each "shore". A and B represent water intakes, one of which is above the "thermocline", i.e., in the warm upper layer while the one on the opposite shore is in the lower cold layer--a common situation in Lake Michigan.

Figure 10-4 depicts a system with a rather high number of nodes across the channel, whereas Figure 10-2 suggested that the number (normally an odd number) is small; 1, 3, or 5, perhaps in combination. If, as seems likely, the rate of frictional damping increases with nodality, the uninodal pattern may be expected to persist longest after a wind disturbance. This will be particularly true of the currents. With decrease in nodality, more of the internal wave energy appears in kinetic form (currents) and less as potential energy (thermocline displacement).

On the assumption that a combination of standing Poincaré waves and nearshore Kelvin waves is an acceptable model for central Lake Michigan, the relationships between thermocline displacements, current direction, and speed are summarized for the uninodal case in Figure 10-15. For the elucidation of these relationships we are indebted to Dr. M. A. Johnson of the National Institute for Oceanography, Wormley, Surrey, England. For conditions near the ends of Lake Michigan, interpretation in terms of models other than rectangular may provide abetter fit with the observations; for instance, a semicircular portion (involving Bessel functions) closing the end of a long channel, or an elliptical basin of high eccentricity (involving Mathieu functions).

The observations on the Milwaukee-Muskegon section coincided in time (summer 1963) with the maximum deployment of the Project's recording instruments in the Lake. It is, therefore, worthwhile to see how far each set of observations can aid in the interpretation of the other.

The positions of the stations considered, for which both temperature and current data were available and which were closest to the railroad ferry track, are given in Table 10-1. The stations were: 17, M_2 (Mortimer's anchor station), and 20, near the ferry track, and station 15, 49 km to the south of it.

Local wind observations were provided by station 18 (wind data only) in the form of 2-hourly envelopes of maximum and minimum readings. These are compared (Figures 10-5 and 10-6) with hourly Weather Bureau readings of six land stations. In an attempt to represent the magnitude and timing of the main wind stresses, wind speeds below 9 knots were ignored and higher speeds were plotted on a square-law scale. The principal wind directions are indicated on the Figures. These show good agreement among the stations in the timing of the wind disturbances, but speeds appear to be considerably higher at station 18 than at the land stations. It should be pointed out, however, that the 2-hourly envelopes at station 18 include, by definition, extreme values, whereas hourly readings at the land stations will not normally include extreme values. The square-law presentation considerably exaggerates this difference. Nevertheless, there seems little doubt that speeds were higher over the water than over land.

Detailed comparison between wind at station 18 and current and temperature fluctuations at stations 15, 17, and 20 were compiled (Figures 10-7 through 10-14) for 15-day intervals within the period July 16 through August 30, 1963. The Figures display the following variables: temperature at two depths for stations 15 and 17 and at four depths for station 20; and, for all stations, 2-hour envelopes of current direction and speed at one depth. These take the form of vertical lines joining the extreme high and low values and covering the range of variation in current direction for each 2-hour period. Current directions are those toward which the current is flowing (and this also applies to Figure 10-15) and wind directions are those from which the wind is coming. The Figures, which present a lot of information in compressed form, show many significant correlations and points of interest, only a few of which can be touched upon here.

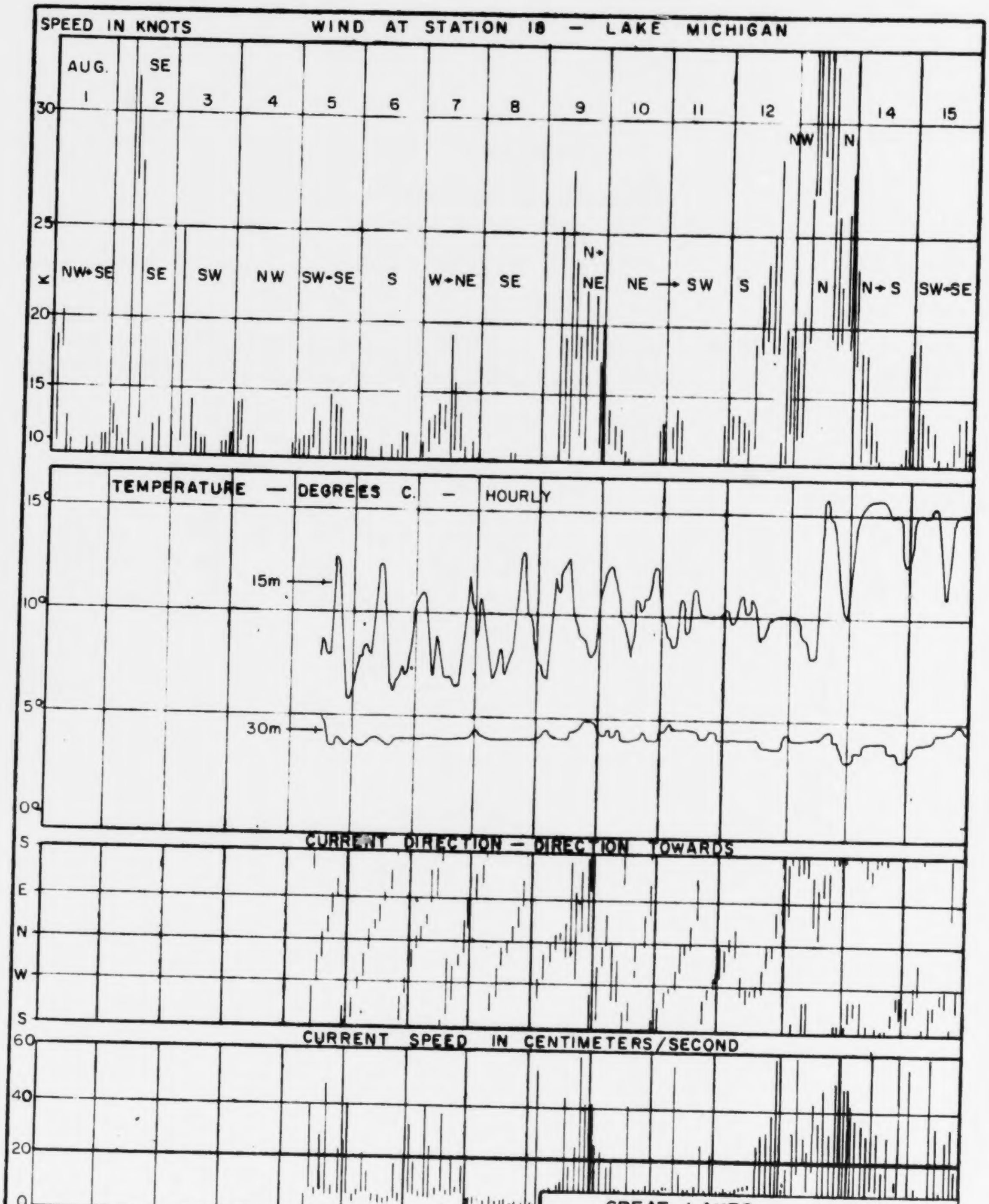
Station positions are listed in Table 10-1. Of the Project's two stations near the railroad ferry track, one, station 17, was close inshore and the other, station 20, although not in midlake, was more representative of open lake conditions. The same can be said of station 15, some 49 km south of the track.

As expected from its location 4 km from a N-S shore, station 17 frequently alternates between southerly and northerly currents, strongly dependent on wind direction and showing a fairly rapid response to wind changes, for instance August 22-26 (Figure 10-11). However, in spite of shore proximity, there were quite long intervals of rotary currents

TABLE 10-1

POSITIONS OF STATIONS

STATION	LATITUDE °N	LONGITUDE °W	DISTANCE (KM) FROM W SHORE	DISTANCE (KM) FROM MILWAUKEE-MUSKEGON RAILROAD FERRY TRACK
17	43°08'	87°51'	4	12 N
18 (wind records only)	43°08'	87°25'	39	7 N
M_2 (MV Cisco anchor station)	43°14'	87°08'	63	12 N
			FROM E SHORE	
20	43°08'	86°32'	18	6 S
15	42°44'	86°36'	31	49 S



TEMPERATURE AND CURRENT AUG. - 1963

AT STATION 15

CURRENTS AT 22 m DEPTH

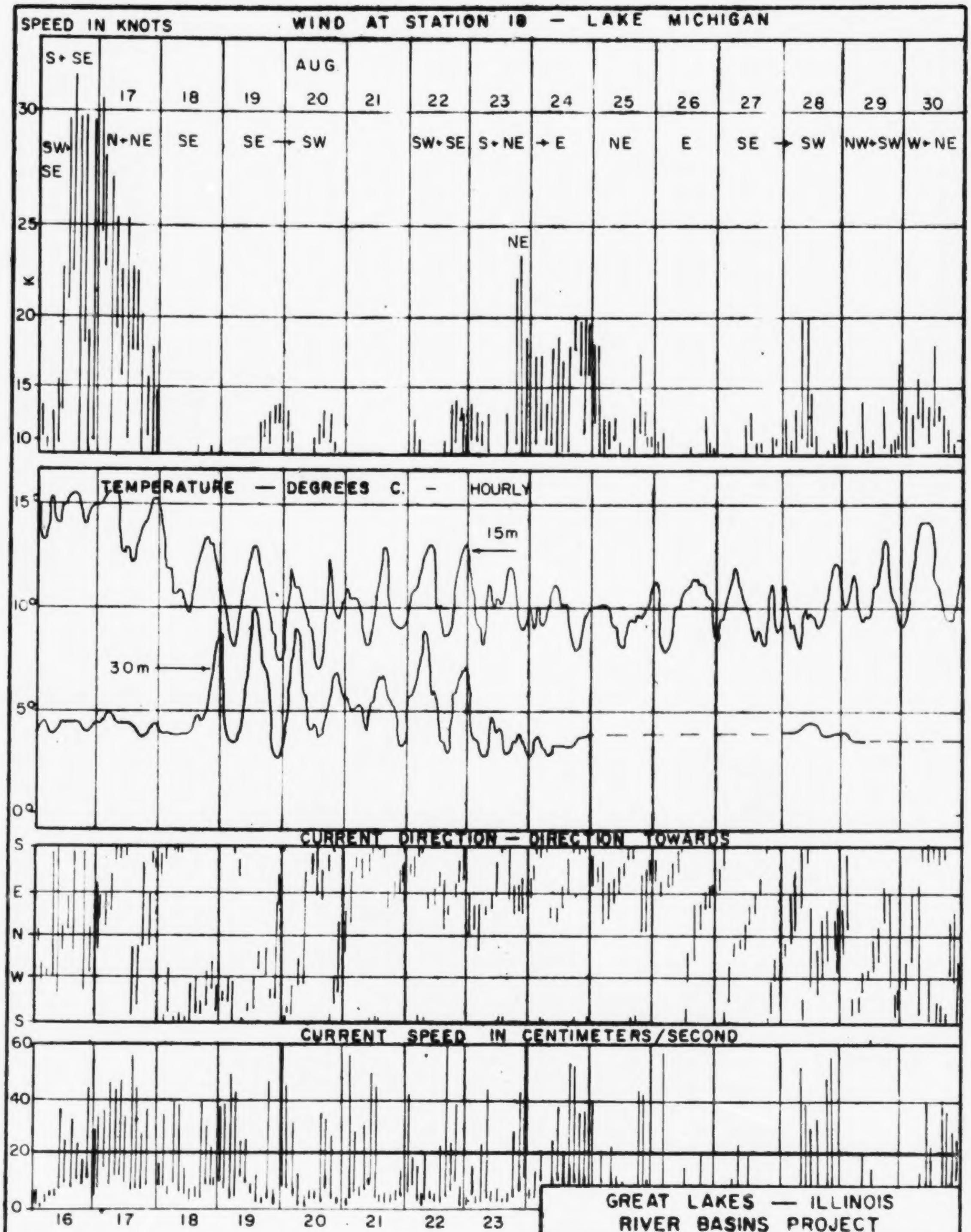
TWO HOUR ENVELOPES — WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS - STA. 15

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 10-7



TEMPERATURE AND CURRENT AT STATION 15

AUG. – 1963

CURRENTS AT 22 m DEPTH

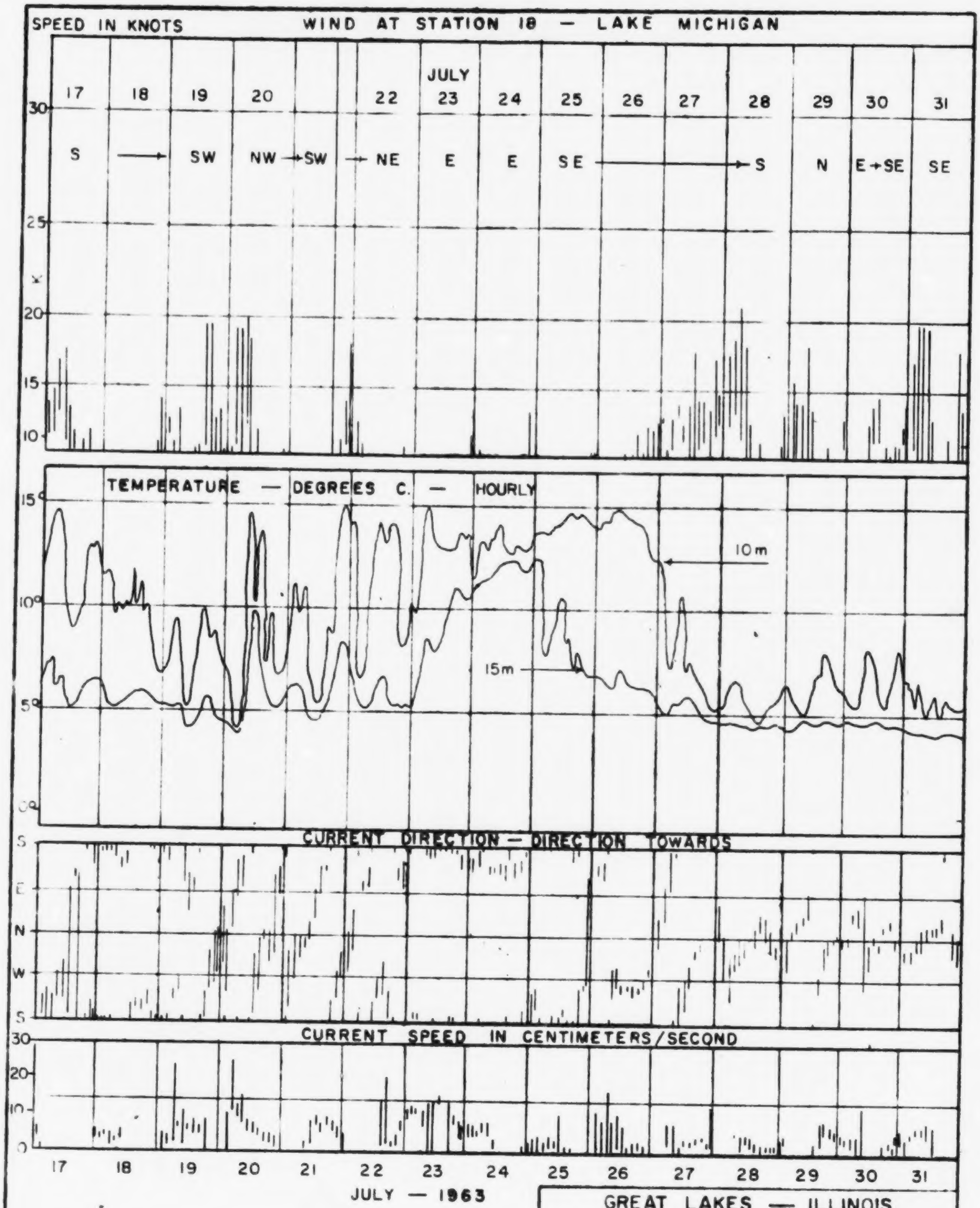
TWO HOUR ENVELOPES – WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO TEMPERATURE & CURRENTS – STA. 15

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Illinois

FIGURE 10-8



TEMPERATURE AND CURRENT

AT STATION 17

CURRENTS AT 15 m DEPTH

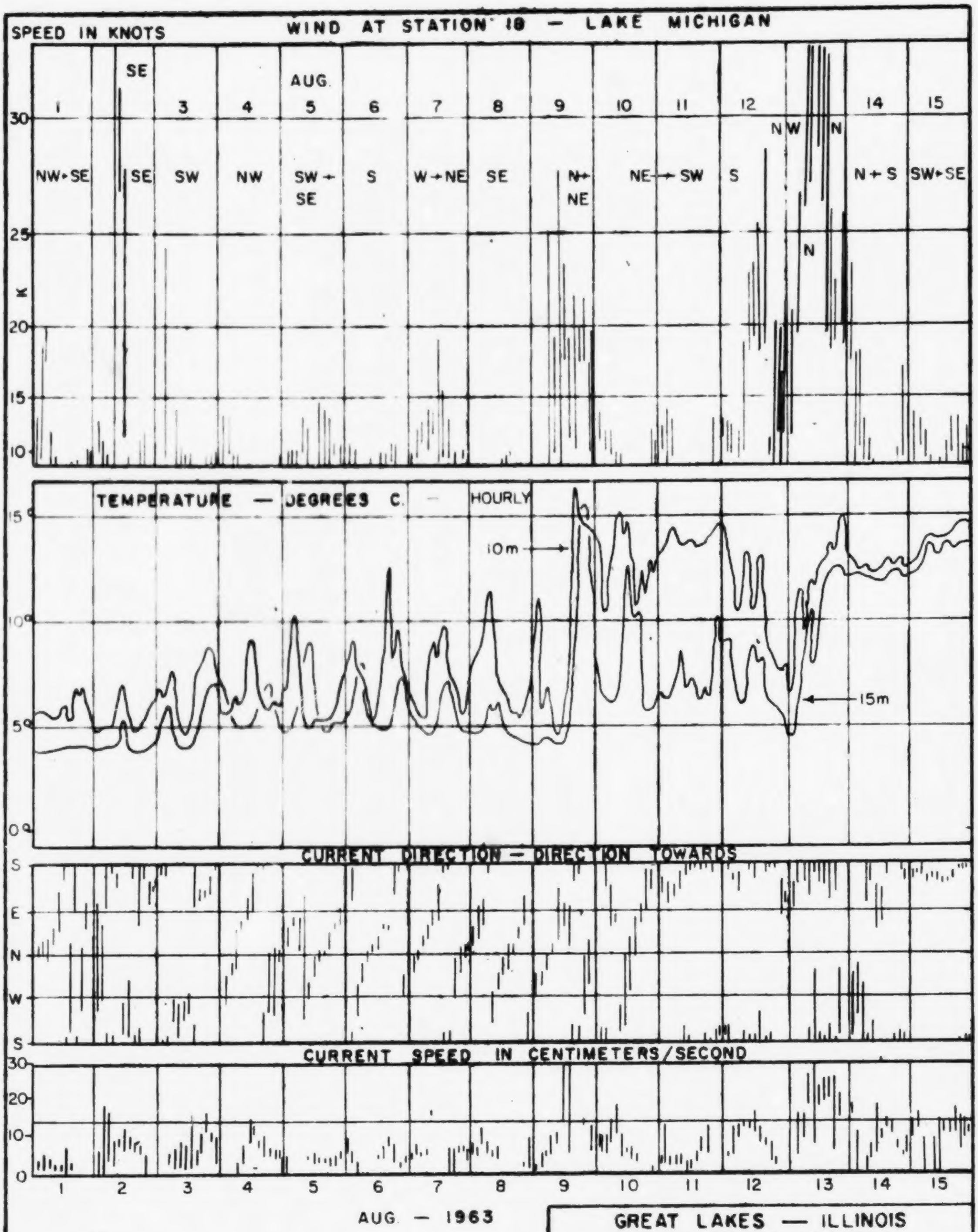
TWO HOUR ENVELOPES — WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS — STA. 17

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN.
Great Lakes Region Chicago, Ill. [illegible]

FIGURE 10-9



TEMPERATURE AND CURRENT

AT STATION 17

CURRENTS AT 15 m DEPTH

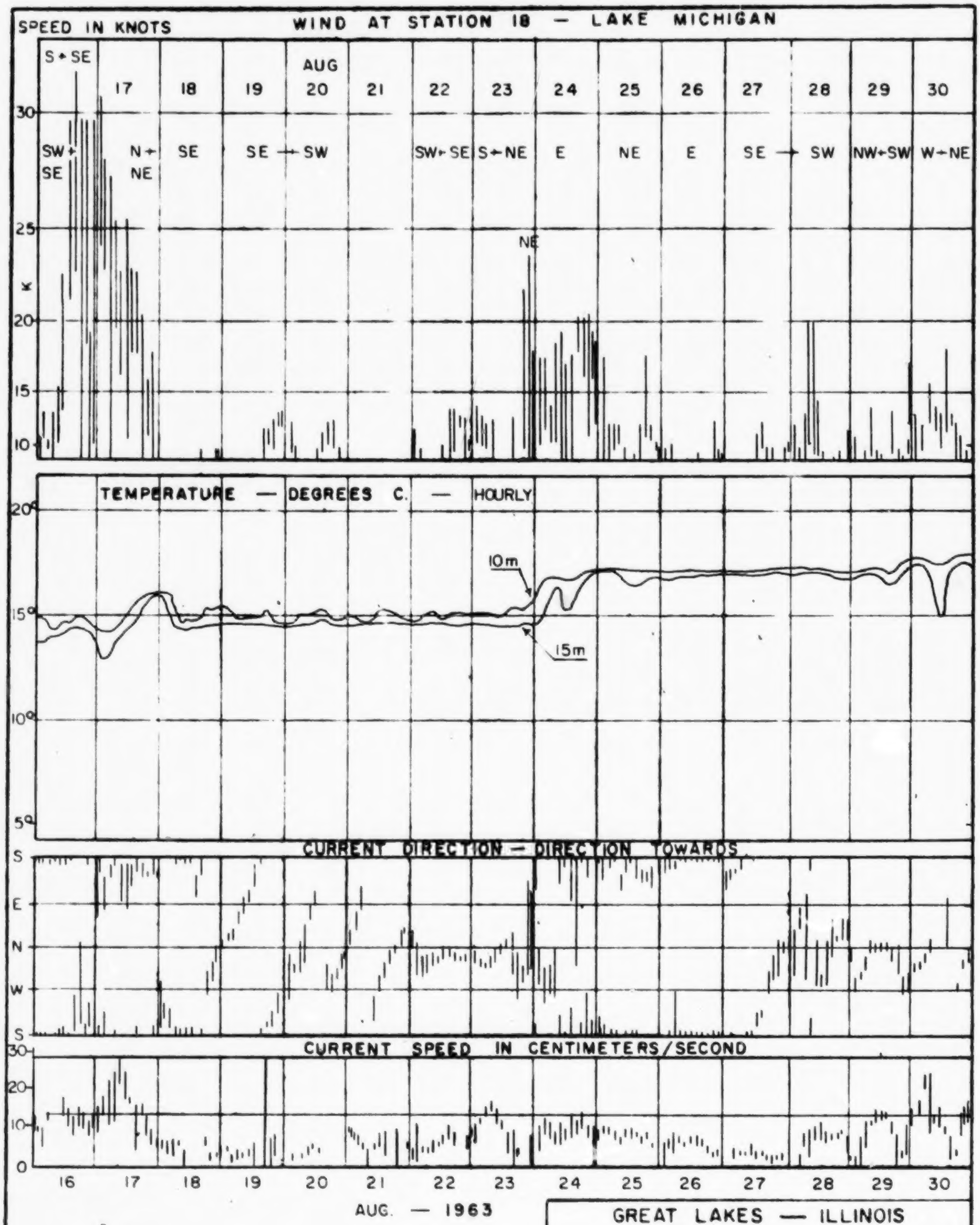
TWO HOUR ENVELOPES - WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS - STA.17

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region **Chicago, Illinois**

FIGURE 10-10



TEMPERATURE AND CURRENT

AT STATION 17

CURRENTS AT 15 m DEPTH

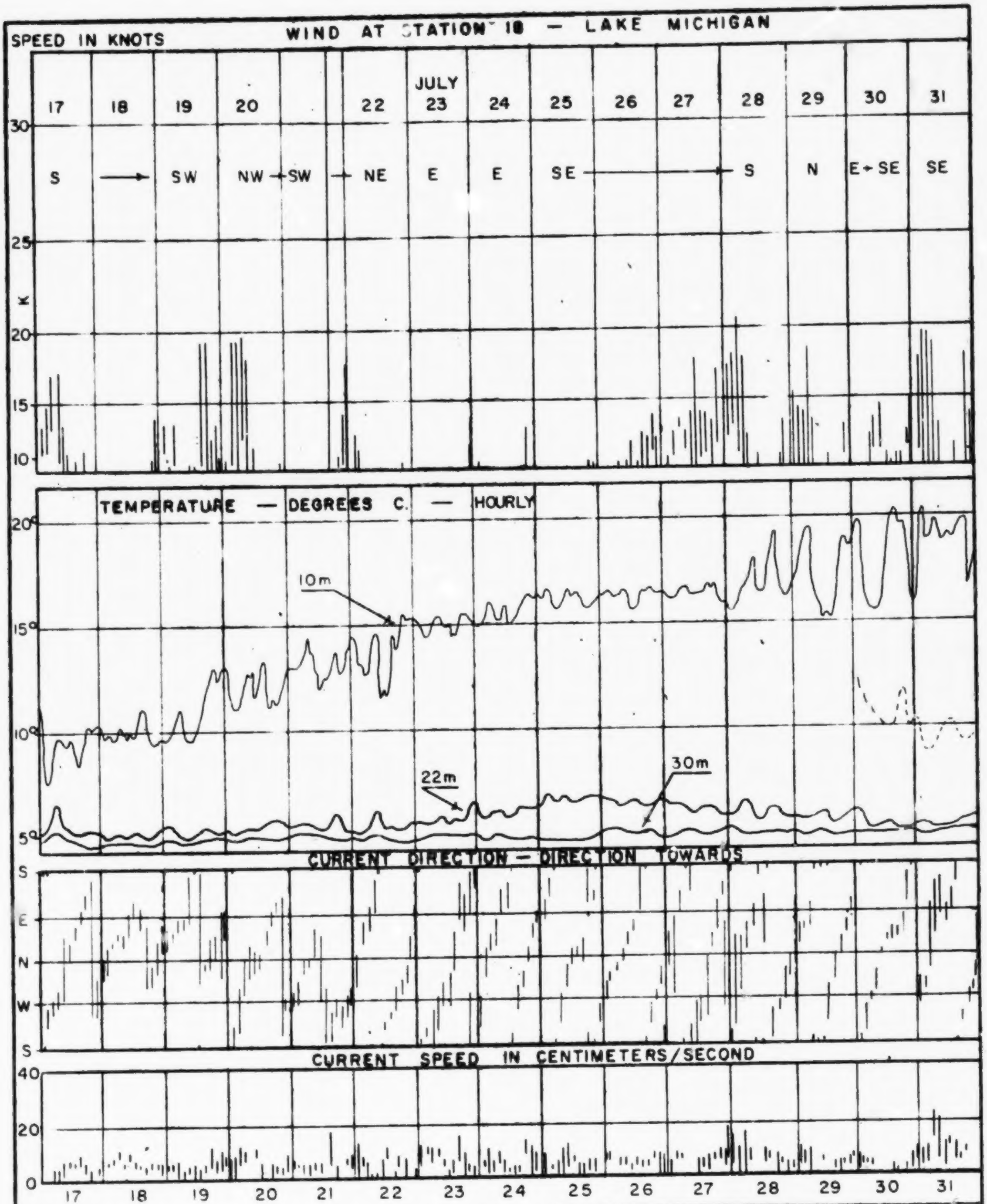
TWO HOUR ENVELOPES — WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS – STA. 17

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 10-11



TEMPERATURE AND CURRENT

AT STATION 20

CURRENTS AT 60m DEPTH

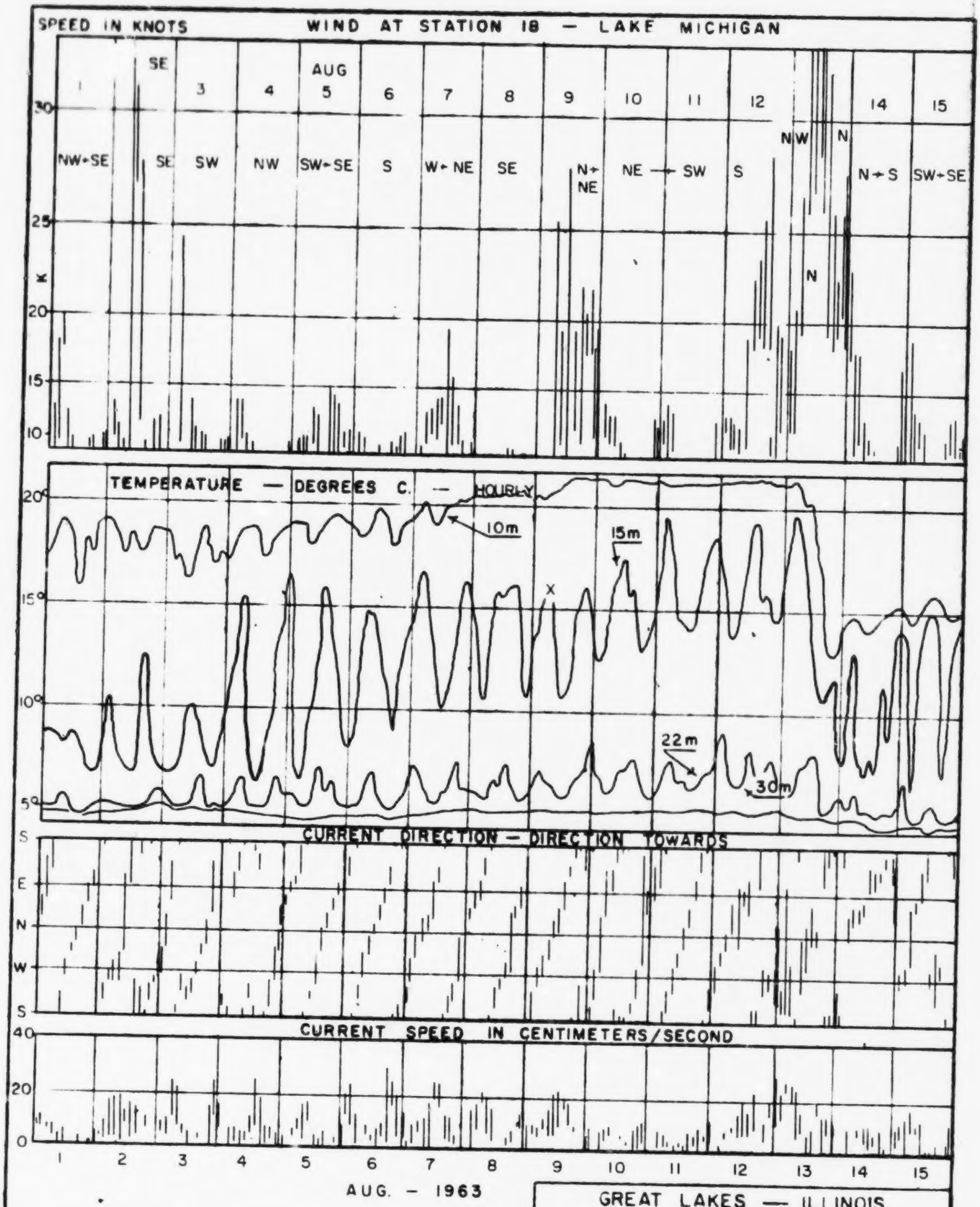
TWO HOUR ENVELOPES – WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS - STA. 20

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 10-12



TEMPERATURE AND CURRENT

AT STATION 20

CURRENTS AT 60 m DEPTH

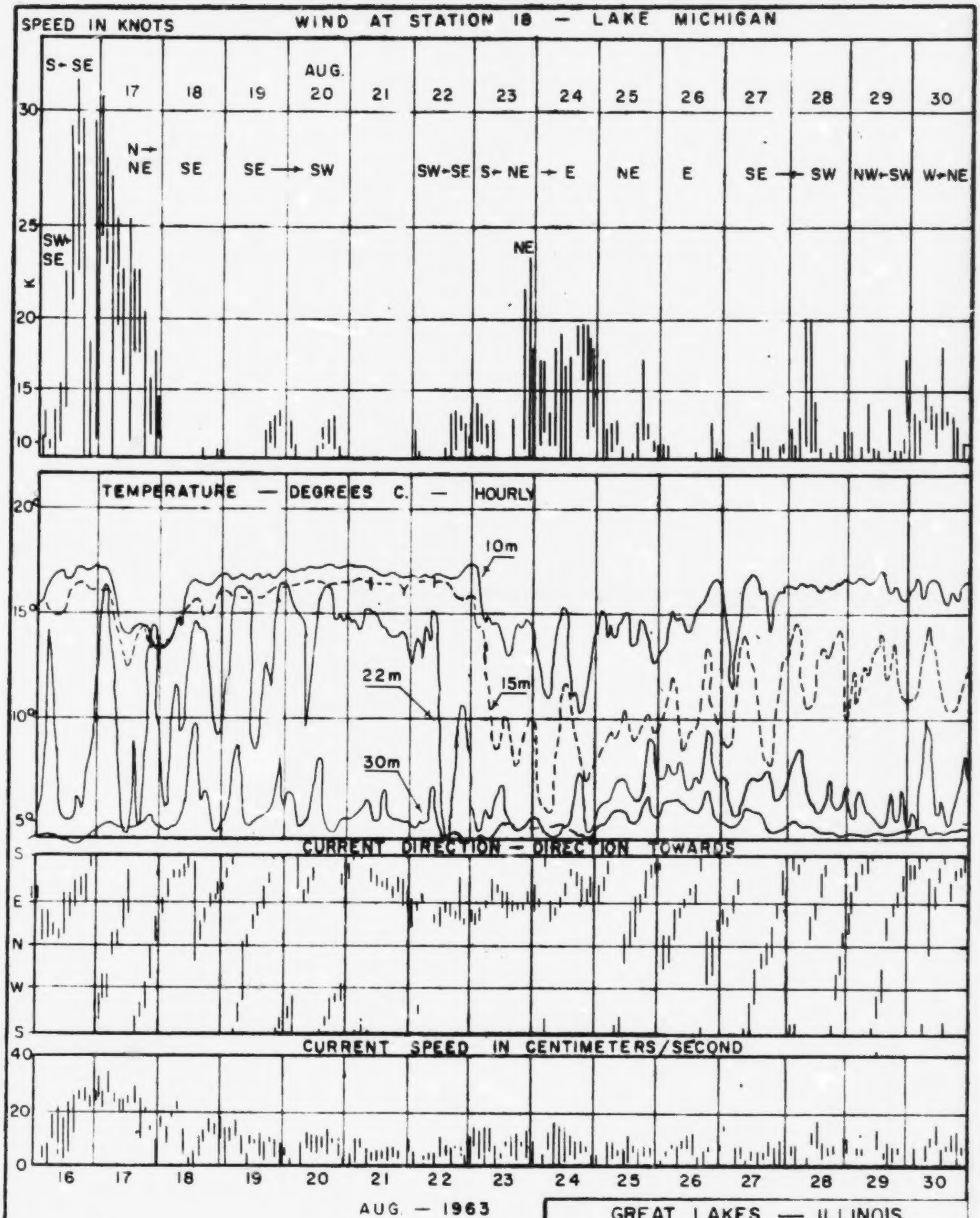
TWO HOUR ENVELOPES — WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS - STA. 20

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 10-13



TEMPERATURE AND CURRENT

AT STATION 20

CURRENTS AT 60 m DEPTH

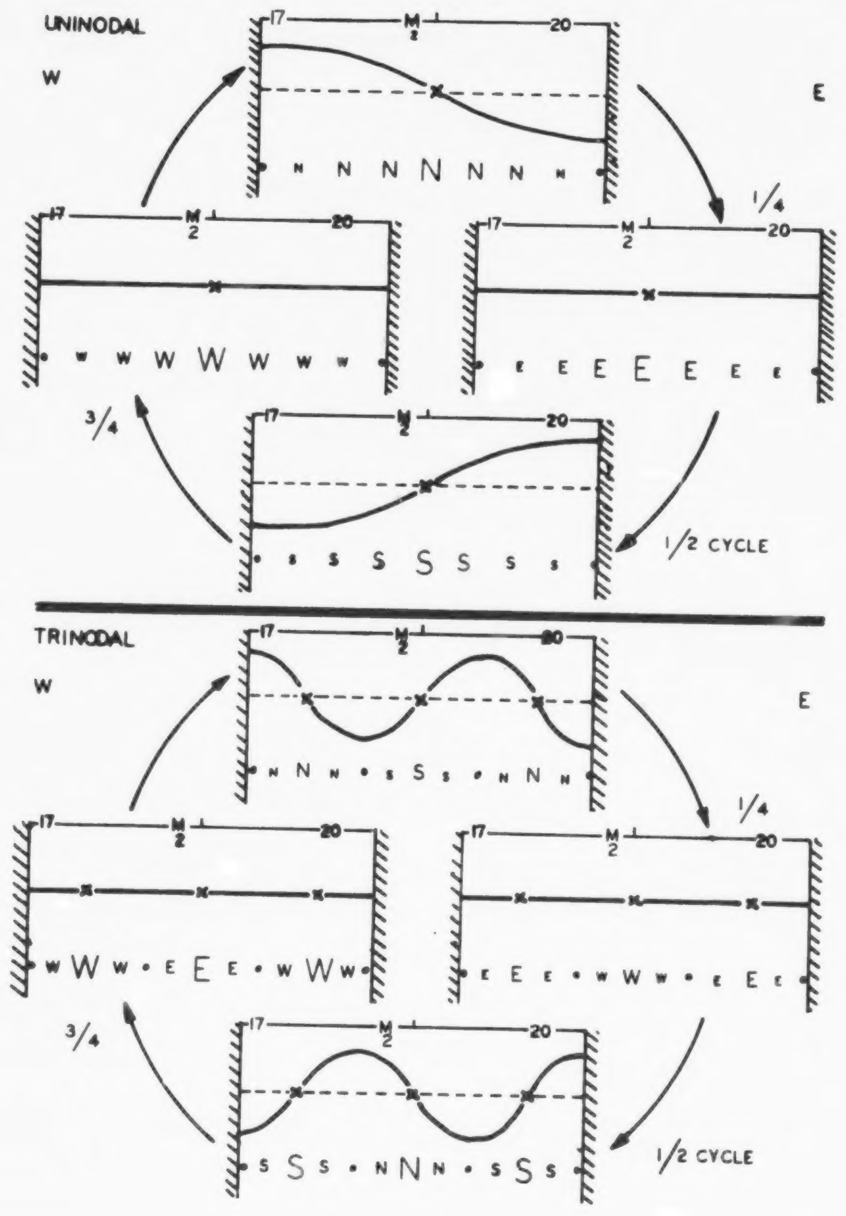
TWO HOUR ENVELOPES — WIND & CURRENT

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

WIND AT STATION 18 COMPARED TO
TEMPERATURE & CURRENTS - STA. 20

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago, Illinois

FIGURE 10-14


UNINODAL
W
E
17
M/2
20
N N N N N N N
1/4
W W W W W W W
E E E E E E E
3/4
S S S S S S S
1/2 CYCLE
TRINODAL
N N N • S S S • N N N
W W W • E E E • W W W
E E E • W W W • E E E
S S S • N N N • S S S

SECTIONS, AT QUARTER CYCLE PHASE INTERVALS, ACROSS A UNINODAL AND TRINODAL STANDING POINCARÉ WAVE IN A TWO-LAYERED LAKE, ROTATING COUNTERCLOCKWISE, REPRESENTING A SECTION ACROSS CENTRAL LAKE MICHIGAN LOOKING NORTH.

(Mortimer, unpublished, April, 1967)

GREAT LAKES — ILLINOIS
RIVER BASINS PROJECT

SECTIONS ACROSS a UNINODAL
and a TRINODAL WAVE

U S DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMIN
Great Lakes Region Chicago Illinois

FIGURE 10-15

associated with internal waves (August 4-9, Figure 10-10), or indications of rythmic fluctuation in direction, or the combination of a unidirectional current with rotation (Figure 10-9, July 28-31 and Figure 10-10, August 4-9).

Compared with station 17, the open Lake stations (15 and 20) were dominated by rotary currents for a much greater part of the time and with a more circular current vector envelope (station 20 during early August, Figure 10-13); but there were also occasions, particularly after strong winds, when more or less steady currents prevailed (station 15, Figure 10-7, August 14-15; and station 20, Figure 10-14, August 21-24). In general, the role of the wind in changing thermocline depth and in setting currents and internal waves in motion is evident in the Figures; and these also give information on the relative timing of the responses. It is also apparent that, particularly during intervals of more or less steady flow, the current speeds and the range of speeds at station 15 were much greater than at the other stations.

Another important result which the Figures demonstrate is that, with rare exceptions (station 17, Figure 10-10, August 4-5) temperature fluctuations at any one station, resulting from internal waves, were in phase at all depths (station 15, Figure 10-8, August 18-22; and station 20, Figure 10-13, early August, but see earlier remarks concerning the 15-m trace). From in-phase behavior of this kind it can be inferred that the internal waves are those of the first vertical mode, appropriate to a two-layered system, in which the flow is in one direction in the upper layer and in the opposite direction in the lower layer. This was the current distribution found at the M. V. Cisco anchor station. As mentioned in Chapter 6, there is evidence that the current reversal across the thermocline is not characterized by a layer of zero flow, but that there is a progressive rotation of the current vector, totaling 180°, on passing downward through the thermocline. A clear demonstration of this state of affairs is not provided by the Figures presented here (although there were clear examples at other stations) because, with the exception of station 17 on July 24, and during the latter half of August, the current measuring depths were usually below the thermocline. Perhaps the current behavior during the interval July 24-28 at station 17 when the thermocline moved upward through the current measuring depth (15 m), might be interpreted as a "change-over" of this kind between a southerly current above and a northerly current below the thermocline.

Of particular interest is the opportunity, provided by Figures 10-7 through 10-14, of testing conformity with theoretical predictions derived from the standing Poincaré wave model. A particular period, the interval August 4-7 was selected when the records from stations 17, 20, and 15 showed internal wave activity coupled with rotating currents, and which included part of a M. W. Cisco anchor station series at M_2 in midlake.

To assist the interpretation, Figure 10-15 presents, in simplified form, cross-sectional pictures of thermocline displacement from the equilibrium level, and current distribution in the lower layer, for a transverse uninodal and transverse trinodal internal standing Poincaré wave in a two-layered lake, rotating counterclockwise. It represents a section across Lake Michigan looking north, but for simplicity, internal Kelvin waves or other mechanisms generating inshore currents parallel to the shores have been omitted. The theoretical current distribution in the upper layer will be everywhere 180° out of phase with that indicated for the lower layer, and the current speeds in the two layers will be inversely proportional to the relative layer thicknesses. Only internal waves of the first vertical mode, i.e., appropriate to a two-layered system, are considered. The illustrations, for each nodality, represent one complete cycle of the oscillation at quarter-cycle stages. Letters display the direction toward which the current is flowing and the size of the letter indicates current speed. Dots represent zero current at the antinodes, on the assumption that the section bisects a standing Poincaré wave cell, i.e., passes through the points of maximum elevation and depression of the thermocline. At other sections through the cell the general current distribution is similar, but there are small currents at the shores and at other antinodes, if other antinodes are present (M. A. Johnson, personal communication). The nodes are at the points marked X, and the relative positions of stations 17, M_2 and 20 are indicated.

By inspection of the trinodal case, and dividing the section into adjacent compartments bounded by each antinode and its nearest node, a correlation table can be constructed (Table 10-2, with nodes at X and antinodes at Y), and extended to derive the pattern for any nodality, along the following lines: the uninodal pattern comprises compartments 1 and 2; the binodal pattern comprises compartments 1, 2, 3, and 4; the trinodal pattern is provided by the compartment series 1, 2, 3, 4, 1, 2; the quadrinodal pattern by 1, 2, 3, 4, 1, 2, 3, 4; the quintinodal by 1, 2, 3, 4, 1, 2, 3, 4, 1, 2; and so on. In other words, correlations between thermocline elevation and current directions between a pair of stations can only indicate which nodality is present if the information is combined with knowledge of the geographical positions of the stations and of the observed or presumed position of the nodes. It also appears likely that, at least as far as the currents are concerned, the higher the nodality, the more quickly the wave will die down, leaving the lower nodalities to dominate the scene. A further guideline for Lake Michigan--in which the normal effect of a wind disturbance is to force the thermocline to tilt downward on one shore and upward on the other--is that odd-numbered transverse nodalities will be the rule.

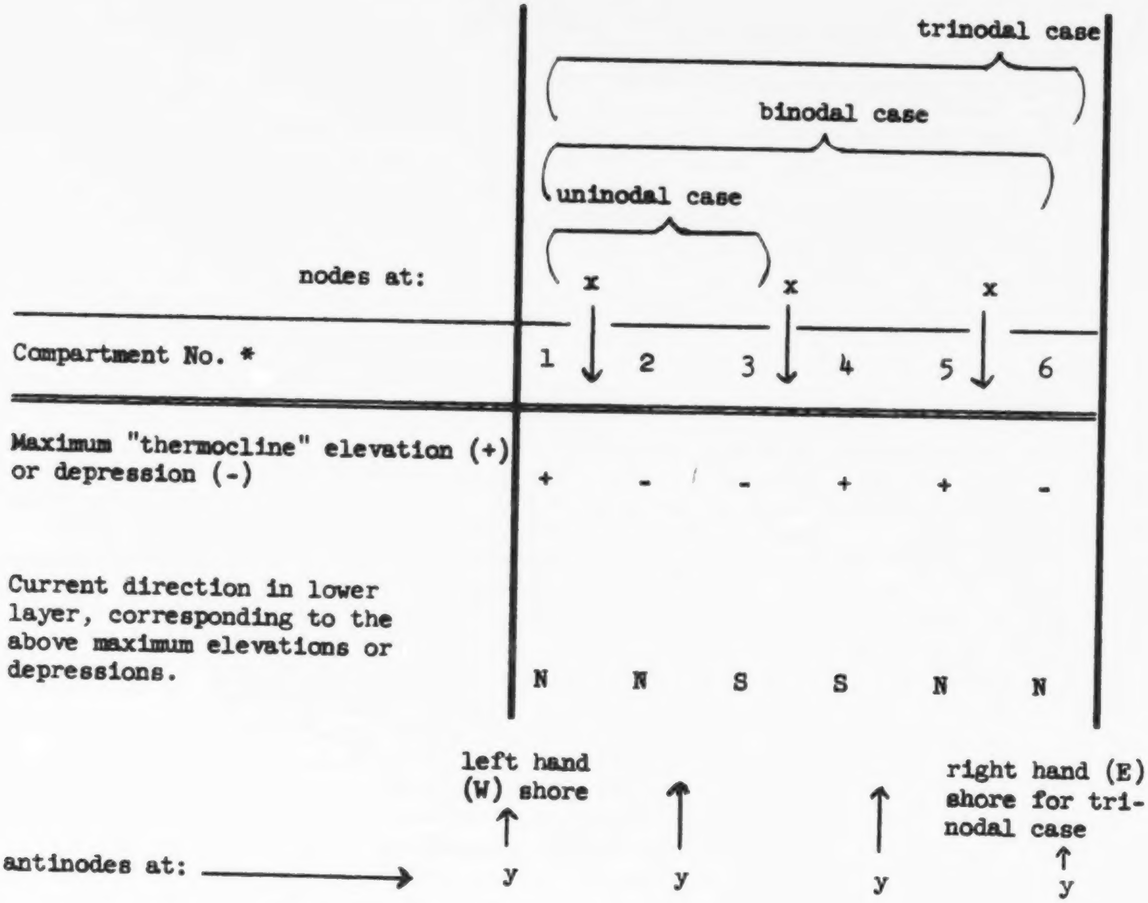
Table 10-3 summarizes, for stations 17, M_2, 20, and 15, during the relatively simple episode, August 4-7, 1963, the temperature and current information needed to make the comparison between theory and events in the Lake. The stations 17 and M_2 form a pair in which the thermocline elevations and lower-layer currents were approximately in phase; and the same is true of the station pair 20 and 15. The two pairs, however, are approximately 180° (i.e., close to 8½ hours or one-half period) out of phase with each other. This result, coupled with the geographical location of these stations, is consistent with a Poincaré wave of transverse nodality one (compare Figure 10-15 upper part) on the assumption that the uninode lies to the east of M_2 (and that there is no longitudinal node between 20 and 15). The next paragraph provides evidence of a uninode to the east of M_2. If the uninodal picture is therefore accepted, the phase relationships between thermocline elevation and current direction at all stations serve to confirm the standing Poincaré wave model, an important result. It will also be noted that a fit with the trinodal case (Figure 10-15, lower part) would be impossible. While--as pointed out in earlier discussion concerning Table 10-2--a fit with some higher nodality than three is conceivable in theory, this would be a most unlikely interpretation, which in any case appears ruled out by consideration of wave period, not discussed here.

During the interval August 4-7, six temperature cross sections were completed using railroad car ferries. When the 10°C isotherms, which represent thermocline depth, are plotted on a common depth/time scale, there is evidence of a node at 76 km from Milwaukee, at which point the depth range of the thermocline did not exceed 2 m over the whole interval. On this occasion, however, the presumed node was less clearly defined than the 66-km node in Figure 10-2, perhaps because the wave amplitudes were then larger, following the storm on August 16-17--and it was also in a different position.

As mentioned earlier, Figure 10-2 for August 19-22 suggests a combined response to a transverse uninodal and trinodal Poincaré wave in which the midlake nodes of each system were coincident at approximately 66 km from Milwaukee. While the temperature records at stations 20 and 15 at that time showed clear indications of internal waves of near-inertial period, set in motion by the storm on August 16-17, the current pattern was too confused to attempt the correlations similar to those carried out above for the August 4-7 episode. It appears that strong unidirectional currents, set in motion by the storm, masked the rotational components. All that can be said with certainty is that the thermocline elevations at stations 20 and 15 were, on this occasion, out of phase, suggesting that there may have been a longitudinal (or transverse) Poincaré node between them. The temperature recorders at station 17 were in the upper layer and a long way from the thermocline;

TABLE 10-2

CORRELATION TABLE FOR STANDING POINCARÉ WAVES OF VARIOUS TRANSVERSE NODALITIES IN A RECTANGULAR TWO-LAYERED BASIN ROTATING COUNTERCLOCKWISE (COMPARE FIGURE 10-15, TRINODAL CASE)


trinodal case
binodal case
uninodal case

nodes at:			x ↓				x ↓				x ↓		
Compartment No. *		1		2		3		4		5		6	
Maximum "thermocline" elevation (+) or depression (-)		+		-		-		+		+		-	
Current direction in lower layer, corresponding to the above maximum elevations or depressions.		N		N		S		S		N		N	
antinodes at: →	left hand (W) shore ↑ y				↑ y				↑ y				right hand (E) shore for trinodal case ↑ y

*See text for definition.

TABLE 10-3

CORRELATION BETWEEN TEMPERATURE 'WAVES' AND CURRENTS AT STATIONS 17, M_2 AND 20 ON OR NEAR THE MILWAUKEE-MUSKEGON SECTION (AND AT STATION 15), AUGUST 4-7, 1963. FOR STATION POSITIONS SEE TABLE 10-1. DATA OBTAINED FROM MORTIMER'S UNPUBLISHED OBSERVATIONS AT M_2 AND ON RAILROAD FERRY SECTIONS, AND BY INSPECTIONS OF FIGURES 10-10, 10-13, AND 10-7.

Station		17	M_2**	20	15
Approximate mean thermocline depth (inspection of ferry transects) -- m		10	18	15-20	17
Depth of temperature record showing greatest amplitude -- m		10	--	15	15
Current measured at -- m (all below thermocline at this time)		15	various	60	22
Approximate hour (C.S.T.) of occurrence of temperature "troughs," assumed equivalent to internal wave "crests":		7	6*		
	4th			15	
		24	23*		
	Aug. 5th			8	
		17			
				1	23
*observed "crests" at M_2	6th	10			
				18	16
		3			
	7th			11	9
		20			
Approximate direction toward which the current was traveling in the lower layer at the above times.		NNE	NNW	SSE	SSE
Approximate mean current speed, cm/sec.		5	10-15	10	15

**M.V. Cisco anchor station.

internal wave indications are therefore unreliable, but such as they are they suggest that station 17 may have been out of phase with station 20. These indications are not conclusive but are not, as far they go, inconsistent with the dominance of a transverse trinodal standing wave pattern on that occasion.

CHAPTER 11

RELATIONSHIP TO WATER USE AREAS

Introduction

Although not all of the initial purposes of this study of water movements in Lake Michigan were accomplished, the information gained will contribute greatly to the development of more effective water pollution control programs for the Great Lakes. For example, planners can now determine the outer limits of diffusion rates in the Lake and the net flow along the shore in the vicinity of an outfall, stream, or water intake.

The wise utilization of the Lake, on a sound technical foundation, has become a reality. The preservation of an acceptable water quality for the future will depend on the course man takes in the disposal of his wastes.

Physical factors affecting water use areas include a broad range of forces which interact to produce a complicated relationship. Fortunately one or two of the factors are usually most dominant and can describe the events which occur. Motions in the Lake can be characterized as either horizontal or vertical. Vertical motions were inferred from thermal gradients. Although vertical currents are very small, the maximum being in the range of 0.06 cm/sec, the distance scale in the vertical is very small when compared to the horizontal scale. Vertical currents may be an order of magnitude greater in the winter than in the summer. Hutchinson (44) shows several instances of summer vertical currents of an order of magnitude greater than those found in Lake Michigan. The currents found in Lake Michigan are primarily a result of displacement of the isotherms due to internal wave motion and consequently result in very little mixing. Horizontal and vertical motions are produced by external, internal, and secondary forces. External forces include: wind, atmospheric pressure, and lunar or solar tide-producing forces. Internal forces can properly be labeled density gradients. These include changes in mass distribution in heat or in dissolved solids. Secondary forces include Coriolis force, friction, turbulence, and centrifugal force. Secondary forces do not produce currents but affect the currents that are produced by other means.

The above forces, whether producing massive turbulence, gentle streamline flow, thermal bars, or thermoclines, influence water uses of the Lake. They can rapidly disperse highly concentrated wastes of a hazardous nature or they can transport them with little mixing to critical water use areas.

The studies reported herein describe conditions under which pollutants will be moved from point to point and permit determination of probable concentrations and effects on water use areas. From this knowledge appropriate pollution abatement measures can be devised to protect and enhance the quality of the Lake waters for all legitimate uses.

Pollutants are discharged or put into Lake Michigan through many sources such as: sewage outfalls, industrial waste discharges, vessel discharges, dumping of dredged material, and storm overflow sewers. In addition, storm-generated waves will resuspend detritus and other pollutants and produce a recycling of these materials. These discharges are the principal sources of waterborne wastes which will affect the users of Lake Michigan water. Although some of the waste sources listed may contribute minimal amounts of pollution, the very long retention period or flowthrough time requires a careful look at all waste sources and the development of a water pollution control program which places appropriate emphasis on future conditions.

Water Use Areas Along Shore

Beach and water intakes along or near the shore will be affected by nearby sources of pollution; proper location and design of waste outlets can minimize such effects. Bottom materials are usually sand in a beach area and normally swept free of settling debris that may be recycled. Likewise, vessel discharges and the dumping of dredged materials will normally occur 3 or more km from most beaches. Storm overflow sewers, sewage outfalls, and industrial waste discharges present the greatest hazards to public bathing.

The steady discharge of pollutants, as a sewage outfall or industrial waste discharge, cannot be compared directly to the occasional once a month, 4- or 5-hour discharge of a storm sewer overflow or the washing of oil tanks once a year. These can be called nonsteady-state and represent pools of pollution. Such problems must receive special consideration.

Based on studies of drogues, the maximum and minimum diffusion factors were calculated for moderately calm conditions, and not critical or minimum diffusion rates. However, if a discharge were part of an oil residue or other oil-based pollutant, little or no dispersion would occur because of the lack of mixing. Therefore, all references to the dispersion or mixing of discharges refer to wastes which are soluble or mix readily with Lake water.

At 150 m (500 feet) from the source, under minimum mixing conditions (calm periods), a pollutant will be at or near 100 percent of its original concentration. At 750 m (2,500 feet) the pollutant will be 20 percent of its original concentration, and at 1,500 m (5,000 feet) it will be at 10 percent. Similar values are found for pools or "slugs" of pollutants.

The greater the diffusivity, ω_1, the more a pollutant moves outward and upstream. It can be easily seen from the above percentages why contaminants, such as taste- and odor-producing hydrocarbons, can travel 15,000 m (50,000 feet) and still be 1 percent of their original concentration, and thus cause problems.

Vessel discharges into restricted harbors, such as boat marinas, constitute a potential hazard because of the number of vessels which congregate in a small area. Since most harbors are restricted in area and depth, and have a small entrance, physical factors do not play a large role in dilution or dispersion. Currents or other water motions are nearly nonexistent and stagnant water conditions may prevail. Unless reasonable care is taken to limit the discharge of pollutants these harbors can become severely degraded in a few years. Milwaukee Harbor is an example of such conditions.

Thermal barrier conditions during the fall, winter, and spring period limit the outward extent of the effective mixing volume. This factor appears to be responsible for unusual solids build-up in the nearshore waters during this period. The late spring storms and lake overturn break up the zonation due to the thermal bar and create conditions for effective mixing with the Lake proper. However, during the summer when the thermal bar no longer exists, a similar build-up occurs. Boundary effects, friction, and the southern gyre are probably responsible for the lateral transfer of water along the shore. Upwelling and downwelling in summer are positive signs that this restriction is much weaker than during the winter period.

Water Use Areas in the Lake

Water supply intakes, fish and aquatic life, and recreational boating are some of the more important uses of lake water away from the shoreline. Outfalls or water intakes are fixed positions, rarely more than 6.4 km (4 miles) from shore. The dumping of dredged materials is normally confined to fixed geographical areas and is usually more than 1.6 km (1 mile) from any water intakes. Vessel discharges in such areas are restricted but much is still left to the discretion of the Captain of the ship.

Normally wastes discharged into the Lake have more mixing than a shore-discharged effluent. This arises from the fact that the pollutant can rise through a column of lake water (if the pollutants are lighter) and is continually mixed. If the currents are nearly stationary, then a mass or pool of pollutants can build up and create a potential problem.

Steady currents, of any magnitude, will assist in the dispersion of pollutants discharged into the Lake. However, during summer periods, the thermocline acts as a barrier against mixing, and all effluents discharged above the thermocline will normally not be dispersed into the lower levels unless density is an additional factor.

The sum total of the effects of physical factors indicates that if the quality of lake waters is to be maintained for all legitimate uses, indiscriminate discharges of wastes must be eliminated or placed under strict control.

Significant Factors

There are several physical factors which contribute significantly to the dispersion (or lack of dispersion) of pollutants. The processes not previously identified in Lake Michigan and determined by Project studies are:

1. Diffusion coefficients. The maximum value found was $\omega_1 = 0.4$ and minimum $\omega_1 = 0.2$. In an area of convergence the minimum may be as low as $\omega_1 = 0.08$. These values represent the outer limits of diffusion.

2. Inshore zonation of suspended materials. Materials discharged into the inshore zone, 0 to 6 km, will normally tend to remain in the zone. During the late fall and early spring a thermal barrier condition restricts the normal diffusion between inshore and offshore waters. The thermal gradients are assisted by the fact that as one approaches the shore the water movements tend to parallel the shore rather than move in any direction under the wind influence. In summer this conformality of flow, due to boundary conditions, is enhanced by the tilting of the thermocline and the existence of the southern gyre creating other artificial boundaries.

3. Lake Michigan has a winter thermocline at the 120- to 180-m level which restricts turnover in the deep central basin. Although a lake turnover does not appear to occur in this basin every year, it no doubt occurs at least once every 10 years. The southern basin mixes from top to bottom every year.

4. No permanent type of circulation pattern exists in the Lake, but four general circulation patterns exist, depending on wind regimes. Ice conditions on the Lake are sporadic and are rarely 100 percent (perhaps once in 30 years). A complete ice cover preventing random wind action permits the formation of true inertia currents which rotate with a period of a half pendulum day. In the summer the internal wave, in the main portion of the Lake, prevents the wind from directly affecting the rotary circulation patterns. A small cellular structure occurs

on the broad circulation patterns and produces a complex interaction between wind and water movement.

5. The summer internal wave on the thermocline begins in late spring and exists until early December. The direction of flow in the epilimnion is generally 180° out of phase with the water in the thermocline and below. The horizontal rotation of the water due to the internal wave exists from top to bottom in the Lake. The motion due to the internal wave is independent of the net circulation pattern which may exist.

6. Wind energy from storms is transmitted through the entire column of water, both in summer and winter. No thermal barrier, such as a thermocline, exists to inhibit energy transfer in the winter--except for the reverse thermocline in the deep hole of the northern basin. In the summer the direct input of energy from a storm excites the internal wave pattern and produces extremely large waves (over 10 meters) and accomplishes some mixing at the thermocline interface. The formation of the large waves in turn appears to transmit into the lowest layers, increasing the speed within the rotating currents proportional to the input. The decay of the energy input is related to friction.

ACKNOWLEDGMENTS

To thank all the people who have contributed to this study would virtually call for a whole new chapter. To those who have assisted directly, the GLIRB Project staff will be always grateful. Noteworthy among these are: Drs. C. H. Mortimer and A. M. Beeton, University of Wisconsin-Milwaukee; Drs. V. E. Noble, J. C. Ayers, D. C. Chandler and F. Bellaire, University of Michigan; Dr. E. Birchfield, Northwestern University; Dr. G. Platzman, University of Chicago; Drs. B. Kinsman and A. Okubo, Johns Hopkins University; Dr. K. Rodgers, University of Toronto; Dr. R. A. Ragotzkie, University of Wisconsin; Dr. F. Webster, Woods Hole Oceanographic Institution; Dr. H. Stommel, Massachusetts Institute of Technology; Dr. W. J. Pierson, E. Mehr and F. Malone, New York University; Dr. R. Gaul, Texas A & M; Dr. D. L. Harris, ESSA; and Mr. T. L. Richards, Department of Meteorology, Canada.

REFERENCES

1. Ayers, J. C., 1956. A Dynamic Height Method for the Determination of Currents in Deep Lakes. Limnology and Oceanography, 1: 150-161.

2. Ayers, J. C., D. C. Chandler, G. H. Lauff, C. F. Powers, and E. B. Henson, 1958. Currents and Water Masses of Lake Michigan. Pub. No. 3, Great Lakes Res. Div., Univ. of Michigan, Ann Arbor, Mich. 169 pp.

3. Ayers, J. C., 1965. The Climatology of Lake Michigan. Pub. No. 12, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich. 72 pp.

4. Batchelor, G. K., 1950. The Application of the Similarity Theory of Turbulence to Atmospheric Diffusion. Quart. J. Roy. Met. Soc., 76: 133.

5. Batchelor, G. K., 1953. The Theory of Homogeneous Turbulence. Cambridge Univ. Press, 197 pp.

6. Bellaire, F. R., 1963. Relation of Winds, Water Levels, and Water Temperatures to Currents in Lake Michigan. Pub. No. 10, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich. 219-230 pp.

7. Bellaire, F. R., 1965. The Modification of Warm Air Moving Over Cold Water. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich. 249-256 pp.

8. Bergstrom, R. E., and G. Hanson, 1962. Great Lakes Basin. AAAS Pub. 71, Washington, D. C. 308 pp.

9. Birge, E. A., 1904. The Thermocline and Its Biological Significance Trans. American Microscopical Society. 25: 5-33.

10. Blackman, R. B. and J. W. Tukey, 1958. The Measurement of Power Spectra. Dover Pub. Inc., New York. 190 pp.

11. Bloust, F. and B. DeCooke, 1960. Comparison of Precipitation on Islands of Lake Michigan with Precipitation on the Perimeter of the Lake. J. Geophysics Res. 65: 1565-1572.

12. Bowden, K. F., 1964. Turbulence. Oceanogr. Mar. Biol. Ann. Rev., 2: 11.

13. Bowden, K. F., 1965. Horizontal Mixing in the Sea Due to a Shearing Current. J. Fl. Mech., 21: 83.

REFERENCES (Continued)

14. Bralove, A. L. and E. I. Williams, 1952. A Study of the Errors of the Bathythermograph. National Sci. Lab., Inc., No. NObsr 52348, 47 pp.

15. Bryson, R. A. and W. W. Bunge, Jr., 1956. The Stress-Drop Jet in Lake Mendota. Limnology and Oceanography, 1: 42-46.

16. Carslaw, H. S. and J. C. Jaeger, 1959. Conduction of Heat in Solids. Oxford Univ. Press, 496 pp.

17. Carter, H. H., 1965. A Method for Delineating an Exclusion Area Around a Sewage Outfall. Chesapeake Bay Institute, Special Report 9, 26 pp.

18. Church, P. E., 1942. The Annual Temperature Cycle of Lake Michigan. Inst. of Met., Univ. of Chicago. Misc. Report No. 4.

19. Church, P. E., 1945. The Annual Temperature Cycle of Lake Michigan. Inst. of Met., Univ. of Chicago. Misc. Report No. 18.

20. Church, P. E., 1946. Annual Temperature Cycle of Lake Michigan. Abstract. Transactions American Geophysical Union, 27: 109-110.

21. Corrsin, S., 1961. Turbulent Flow. American Scientist, 49: 300-325.

22. Csanady, G. T., 1963. Turbulent Diffusion in Lake Huron. J. Fl. Mech., 17: 360.

23. Csanady, G. T., 1964. Turbulence and Diffusion in the Great Lakes. Pub. No. 11, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich. 326-339.

24. Day, P. C., 1926. Precipitation in the Drainage Area of the Great Lakes, 1875-1924. Mo. Wea. Rev., 54: 85-106.

25. Deason, H. J., 1932. A Study of Surface Currents in Lake Michigan. The Fisherman, 1 (5): 3-4, 12.

26. Deason, H. J., 1936. Bottles Set Adrift on Lake Michigan Yield Information on Surface Currents. Mich. Cons., 6 (6).

27. Dixon, W., and F. Massey, 1959. Introduction to Statistical Analysis. McGraw-Hill, N. Y., 228 pp.

REFERENCES (Continued)

28. Donn, W., and M. Ewing, 1956. Stokes' Edge Wave in Lake Michigan. Sci., 124: 1238-1242.

29. Eklund, H., 1963. Fresh Water: Temperature of Maximum Density Calculated from Compressibility. Sci., 142 (3598): 1457-1458.

30. Emery, K. O., 1951. Bathymetric Chart of Lake Michigan. Univ. of Minn. Tech. Paper No. 77.

31. Farlow, J. S., 1965. A Field Technique for Horizontal Diffusion Studies in Lakes Michigan and Erie. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich. 299-303 pp.

32. Feyling, A. F., 1962. Geodyne Temperature Recorder. Geodyne Corp.

33. Frantz, D. and R. Putz, 1962. Unsolicited Proposal for an Untended Current, Temperature and Wind Data Acquisition System. Marine Advisers and ORE, Inc.

34. Gaul, R., J. Snodgrass, and D. Cretzler, 1963. Some Dynamical Properties of the Savonius Rotor Current Meter. Marine Sciences Instrumentation, Vol. 2, ISA, Plenum Press, New York.

35. Haines, D. A., and R. A. Bryson, 1961. An Empirical Study of Wind Factor in Lake Mendota. Limnology and Oceanography, 6: 356-364.

36. Harrington, M. W., 1895. Surface Currents of the Great Lakes. U. S. Dept. of Agriculture, Weather Bur. Bull. B.

37. Hazen, H. A., 1883. Report on Wind Velocities at the Lake Crib and at Chicago. Signal Service Notes No. VI, 20 pp.

38. Hinze, J. O., 1959. Turbulence, McGraw-Hill Book Co., Inc., 586 pp.

39. Holleyman, J. B., 1966. Some Results of the Program Conducted by the Great Lakes-Illinois River Basins Project on the Great Lakes. Pub. No. 15, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 323-331 pp.

40. Hough, J. L., 1958. Geology of the Great Lakes. Univ. of Ill. Press, Urbana, Ill.

REFERENCES (Continued)

41. Hughes, L., 1965. Predictions of Surges in the Southern Basin of Lake Michigan. Mo. Wea. Rev., 93 (5): 292-296.

42. Hunt, G. S., 1962. Water Pollution and the Ecology of Some Aquatic Invertabrates in the Lower Detroit River. Pub. No. 9, Great Lakes Res. Div., Univ. of Mich., 10.

43. Hunt, I. A., 1959. Winds, Wind Set-Ups, and Seiches on Lake Erie. U. S. Lake Survey, Detroit, Mich., 59 pp.

44. Hutchinson, G. E., 1957. A Treatise on Limnology, Vol. 1: Geography, Physics and Chemistry. John Wiley & Sons, Inc., N. Y. 1015 pp.

45. Johnson, J. H., 1960. Surface Currents in Lake Michigan 1954 and 1955. U. S. Fish and Wildlife Service Special Scientific Report, Fisheries No. 338.

46. Joseph, J. and H. Sendner, 1958. Uber Die Horizontale Diffusion im Meere. Deutsche Hydrographische Feitschrift, 11: 49-77.

47. Judson, W. V., 1909. Currents in Lake Michigan. First Report of the Lake Michigan Water Commission. Urbana, Ill., 63-68.

48. Kehr, W. Q., and L. Townsend, 1965. A Comprehensive Water Pollution Control Study for the Lake Ontario Basin. Presented to the New York Water Pollution Association, June 1965.

49. Lathbury, A., R. Bryson, and B. Lettau, 1960. Some Observations of Currents in the Hypolimnion of Lake Mendota. Limnology and Oceanography, 5: 409-413.

50. Malone, F., 1967. An Analysis of Current Measurements in Lake Michigan. Technical Report. New York Univ.

51. Mehr, E., 1965. Computer Processing of Lake Data 1963-1964. New York Univ., 45 pp.

52. Millar, F. G., 1952. Surface Temperatures of the Great Lakes. Jour. Fish Res. Bd. Can., 9: 329-376.

53. Moffett, J. W., 1962. An Instance of Upwelling Along the East Shore of Lake Michigan, 1955. Pub. No. 9, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 126 pp.

54. Mortimer, C. H., 1963. Frontiers in Physical Limnology with Particular Reference to Long Waves in Rotating Basins. Pub. No. 10, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 9-42 pp.

55. Mortimer, C. H., 1965. Spectra of Long Surface Waves and Tides in Lake Michigan and at Green Bay, Wis. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 304-325 pp.

56. Noble, V. E., 1961. Measurement of Horizontal Diffusion in the Great Lakes. Pub. No. 7, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 85-95 pp.

57. Noble, V. E., 1965. Growth of Ice on Lake Michigan. II Winter Temperature Structure of Lake Michigan. Great Lakes Res. Div., Ann Arbor, Mich. NSF Grant GP 2411. Manuscript.

58. Okubo, A., 1962. A Review of Theoretical Models for Turbulent Diffusion in the Sea. J. Oceanogr. Soc. Japan, the 20th Anniv. Vol. 286.

59. Ownbey, C. and G. Willeke, 1965. Long-term Solids Build-up in Lake Michigan Water. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich., 141-152 pp.

60. Pritchard, D. W., and J. H. Carpenter, 1960. Measurements of Turbulent Diffusion in Estuarine and Inshore Waters. Bull. Int. Assoc. Sci. Hydrol. (20):37.

61. Ragotzkie, R. A., and M. Bratnick, 1965. Infrared Temperature Patterns on Lake Superior and Infrared Vertical Motions. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 349-357 pp.

62. Richards, T. L., 1964. The Meteorological Aspects of Ice Cover on the Great Lakes. Mo. Wea. Rev., 92: 297-302 pp.

63. Richardson, L. F., 1926. Atmospheric Diffusion Shown on a Distance-Neighbor Graph. Proc. Roy. Soc. London. A 110, 709.

64. Richardson, L. F., and H. Stommel, 1948. Note on Eddy Diffusion in the Sea. J. Met., 5:238-240.

65. Richardson, W. S., 1962. Instruction Manual for Recording Current Meter. Woods Hole Oceanographic Institution, Ref. No. 62-6, 10 pp.

66. Richardson, W. S., P. B. Stimson, and C. H. Wilkins, 1963. Current Measurements from Moored Buoys. Contribution No. 1354, Woods Hole Oceanographic Institution.

67. Rockwell, D. C., 1966. Theoretical Free Oscillations of the Great Lakes. Pub. No. 14, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 352-368 pp.

68. Rodgers, G. K., 1965. The Thermal Bar in the Laurentian Great Lakes. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich. 358-363 pp.

69. Scott, J. T., 1964. A Comparison of the Heat Balance of Lakes in Winter. Tech. Report No. 13, Univ. of Wis., Dept. of Meteorology.

70. Scott, J. T., and R. A. Ragotzkie, 1961. Heat Budget of an Ice Covered Inland Lake. Tech. Report No. 6, Univ. of Wis., Dept. of Meteorology.

71. Shepard, F. P., 1937. Origin of the Great Lakes Basins. J. of Geol., 45: (1):76-88.

72. Shulman, M. D., and R. A. Bryson, 1961. The Vertical Variations of Wind-Driven Currents in Lake Mendota. Limnology and Oceanography, 6: 347-355.

73. Spilhaus, A. F., 1937. A Bathythermograph. J. Mar. Res., 1: 95-100.

74. Stommel, H., 1949. Horizontal Diffusion Due to Oceanic Turbulence. J. Mar. Res., 8: 199-225.

75. Sverdrup, H. U., M. W. Johnson, and R. H. Fleming, 1946. The Oceans. Prentice-Hall, N. Y. 1049 pp.

76. Tate, M. W., and R. C. Clelland, 1957. Non Parametric and Shortcut Statistics. Interstate Printers and Publishers, Inc., Danville, Ill. 171 pp.

77. Thwaites, F. T., 1947. Geomosphiology of the Basin of Lake Michigan. Mich. Academy of Sci., Arts and Letters, 33:243-251.

78. Townsend, C. Mcd., 1913-14. Effect Upon the Climate of the Lake States by a Change in the Natural Current of Lake Michigan. House Doc. 762, 63rd Congress, 2nd Session, App. C. 40-71, Washington, D. C.

REFERENCES (Continued)

79. U. S. Geological Survey. Annual. Surface Water Supply of the United States. (1965) Wisconsin, Michigan, Indiana and Illinois.

80. U. S. Engineers Waterways Exp. Station 1962. Measurements and Telemetry of Current Velocity and Direction. Proj. Bull. 62-1, 8 pp.

81. U. S. Lake Survey, Annual. Average Precipitation in Inches on the Lake Surface of Lake Michigan. Detroit, Mich.

82. U. S. Public Health Service, 1961. Movements in Lake Michigan of Water Discharged September 14, 1961 from the Chicago Sanitary Canal System. U. S. Exhibit No. 4, Chicago Diversion Case.

83. U. S. Weather Bureau, 1959. Evaporation Maps for the United States. Tech. Report No. 37, 13 pp.

84. Van Oosten, J., 1960. Temperatures of Lake Michigan, 1930-32. United States Fish and Wildlife Service Special Scientific Report, Fisheries No. 322.

85. Verber, J. L., 1953a. Surface Water Movements in Western Lake Erie. Ohio J. Sci., 53: 42-46.

86. Verber, J. L., 1953b. Short Time Variation of Temperature in Lake Mendota, Wisconsin. Ohio J. Sci., 53: 72-76.

87. Verber, J. L., 1955. The Climates of South Bass Island, Western Lake Erie. Ecology, 36: 388-400.

88. Verber, J. L., 1964. Initial Current Studies in Lake Michigan. Limnology and Oceanography, 9: (3) 426-430.

89. Verber, J. L., 1965. Current Profiles to Depth in Lake Michigan. Pub. No. 13, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 364-371 pp.

90. Verber, J. L., 1966. Inertial Currents in the Great Lakes. Pub. No. 14, Great Lakes Res. Div., Univ. of Mich., Ann Arbor, Mich., 375-379 pp.

91. Webster, F., 1964. Processing Moored Current Meter Data. Tech. Ref. No. 64-55. Woods Hole Oceanographic Institution.

92. Welch, P. S., 1948. Limnological Methods. Blakiston Co., Philadelphia, 381 pp.

REFERENCES (Continued)

93. Welch, P. S., 1952. Limnology. McGraw-Hill Book Co., Inc., N. Y., 538 pp.

94. Williams, G. C., 1964. Evaluation of Buoy Wind Data from Four Adjacent Stations on Southern Lake Michigan During September and October 1963. Unpublished.